

Applications of intense low-energy ISOL beams

**Ulli Köster
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**NEUTRONS
FOR SCIENCE**

Potpourri of thoughts on ISOL@MYRRHA

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NEUTRONS
FOR SCIENCE

Optimize event rate

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}}$$

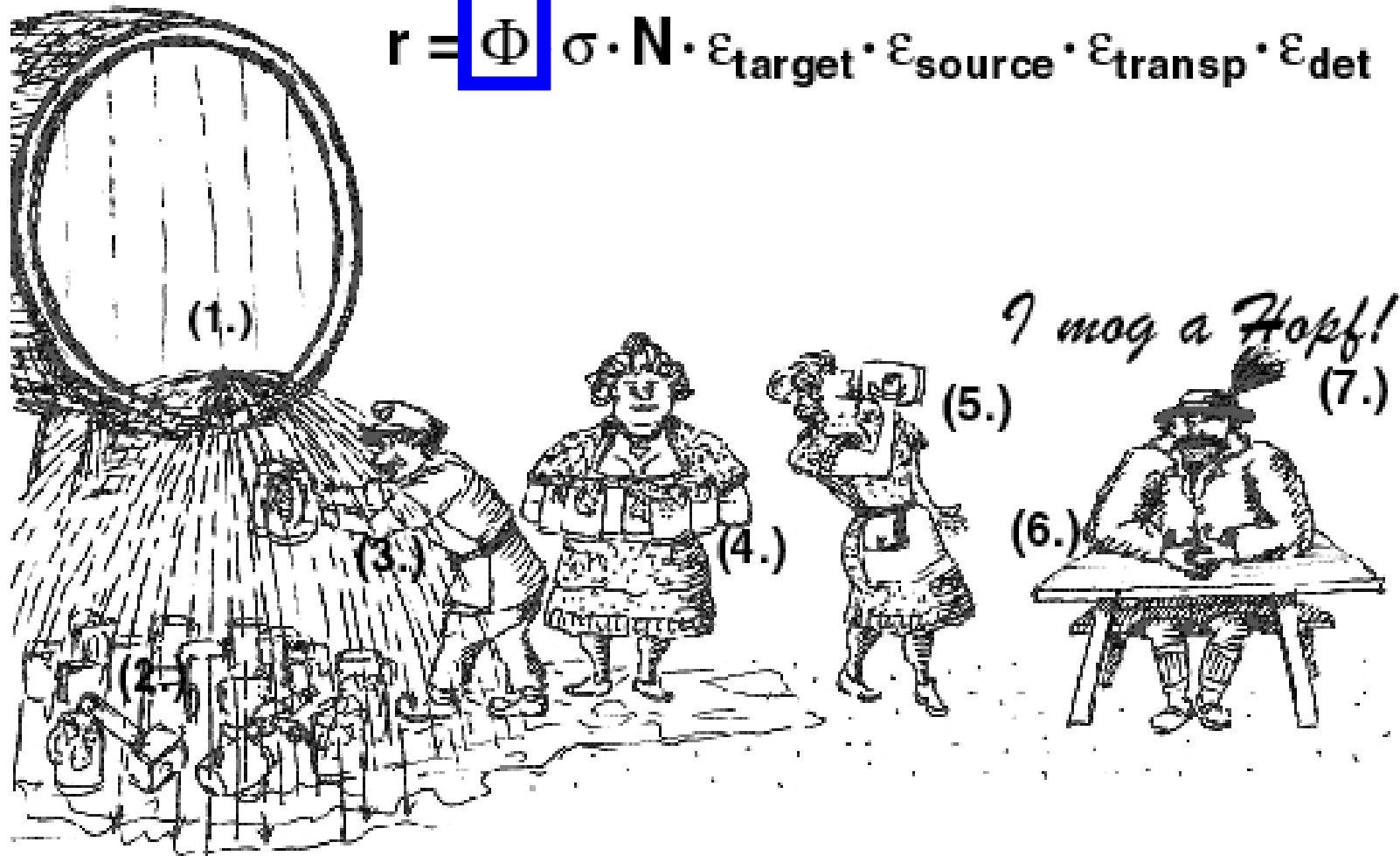

In-target production


Efficiency

Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}}$$



No free beer!

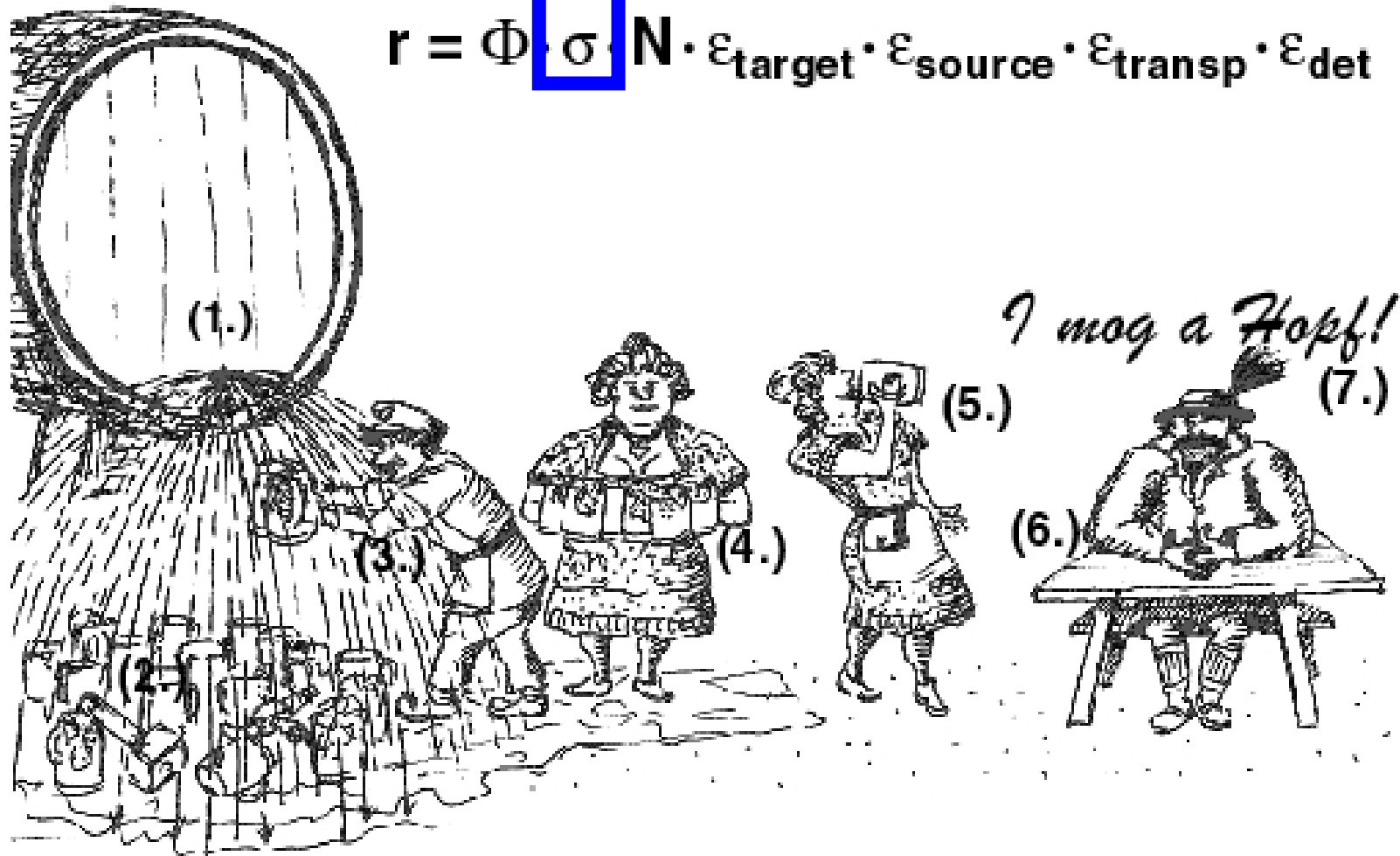


- shielded target station
- target handling (joint use of common hot cell with MYRRHA?)
- handling of volatile radioactivity
- disposal of activated targets
- ...
- running costs + personnel

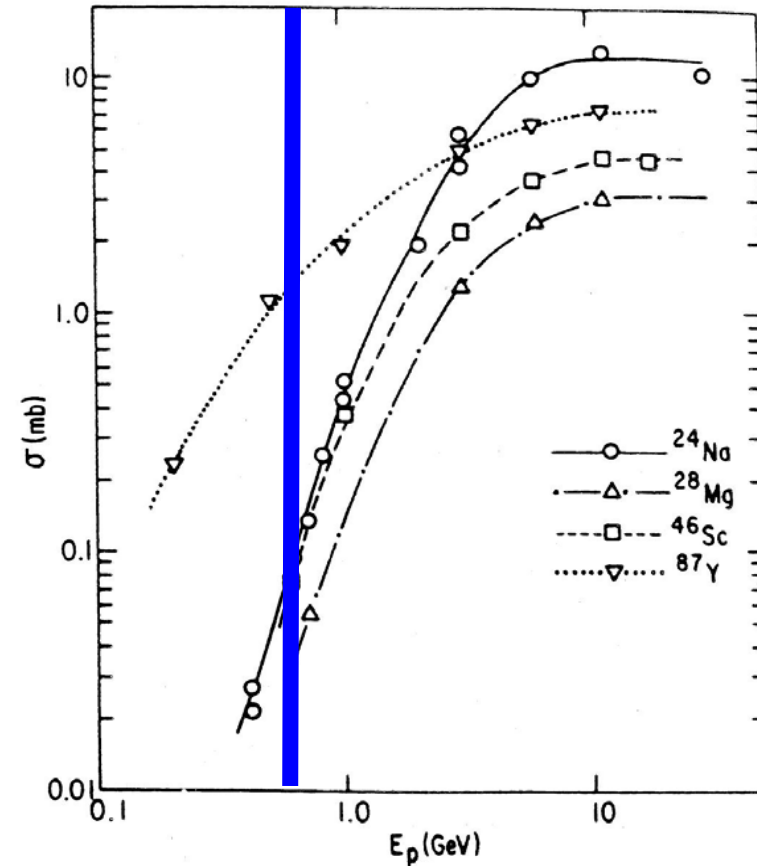
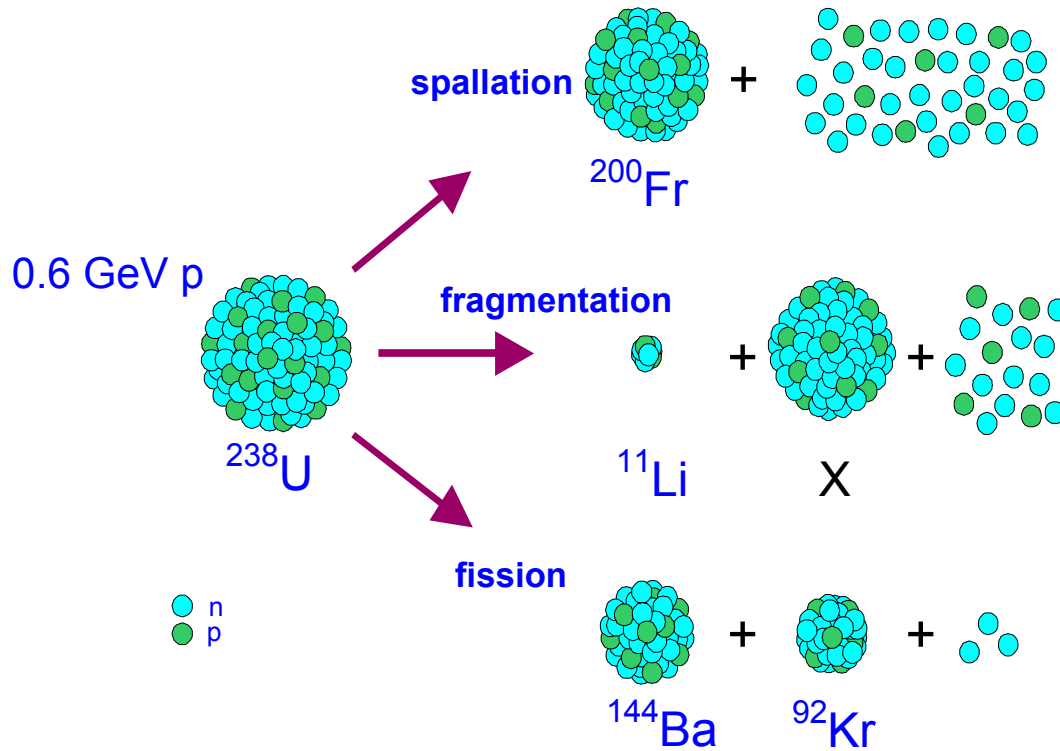
Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \cdot \epsilon_{\text{source}} \cdot \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}}$$



High energy nuclear reactions



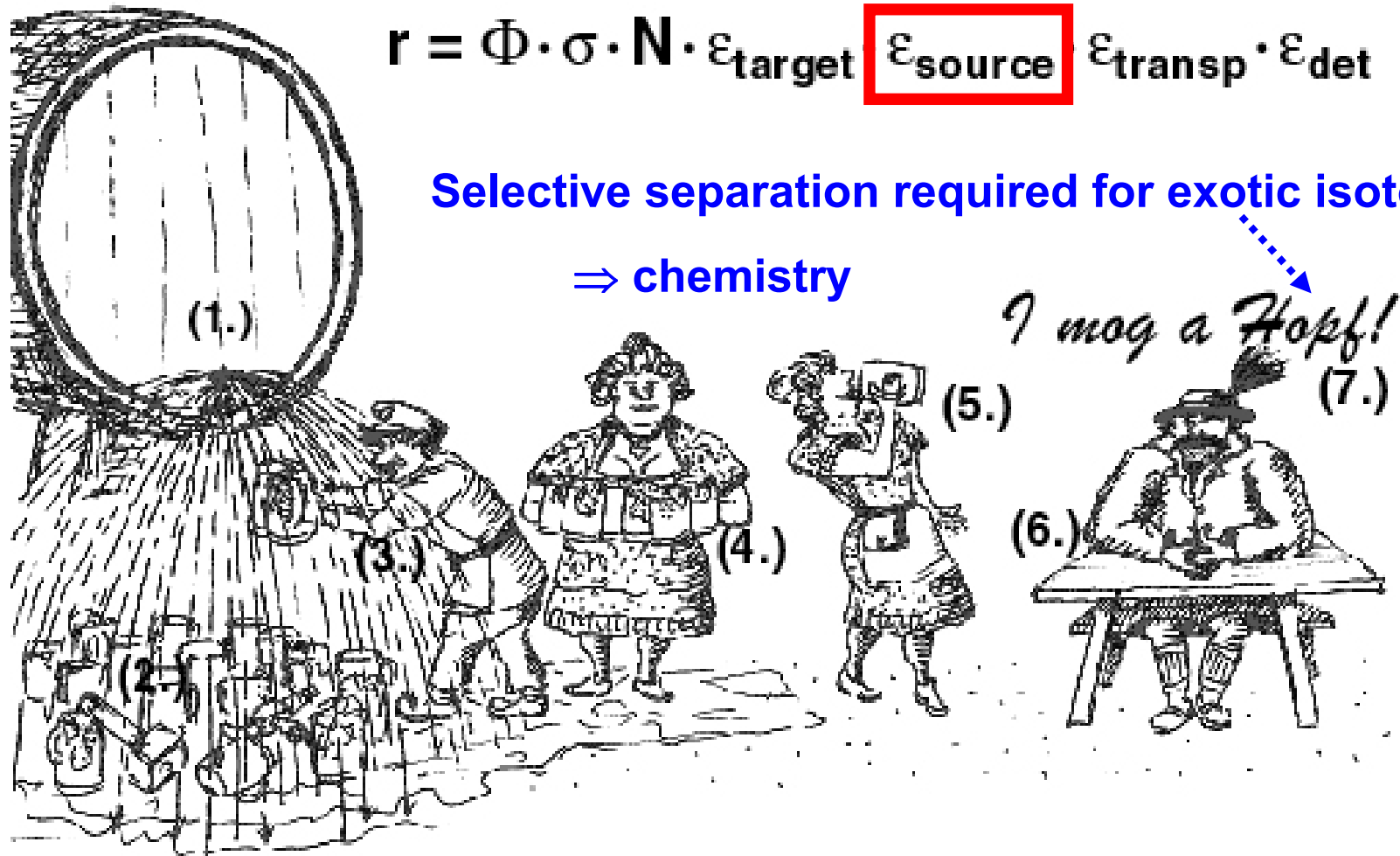
Optimize RIB intensity and purity

All steps of the separation chain need to be optimized!

$$r = \Phi \cdot \sigma \cdot N \cdot \epsilon_{\text{target}} \epsilon_{\text{source}} \epsilon_{\text{transp}} \cdot \epsilon_{\text{det}}$$

Selective separation required for exotic isotopes!

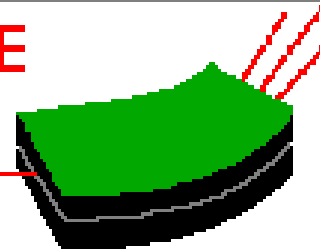
⇒ chemistry



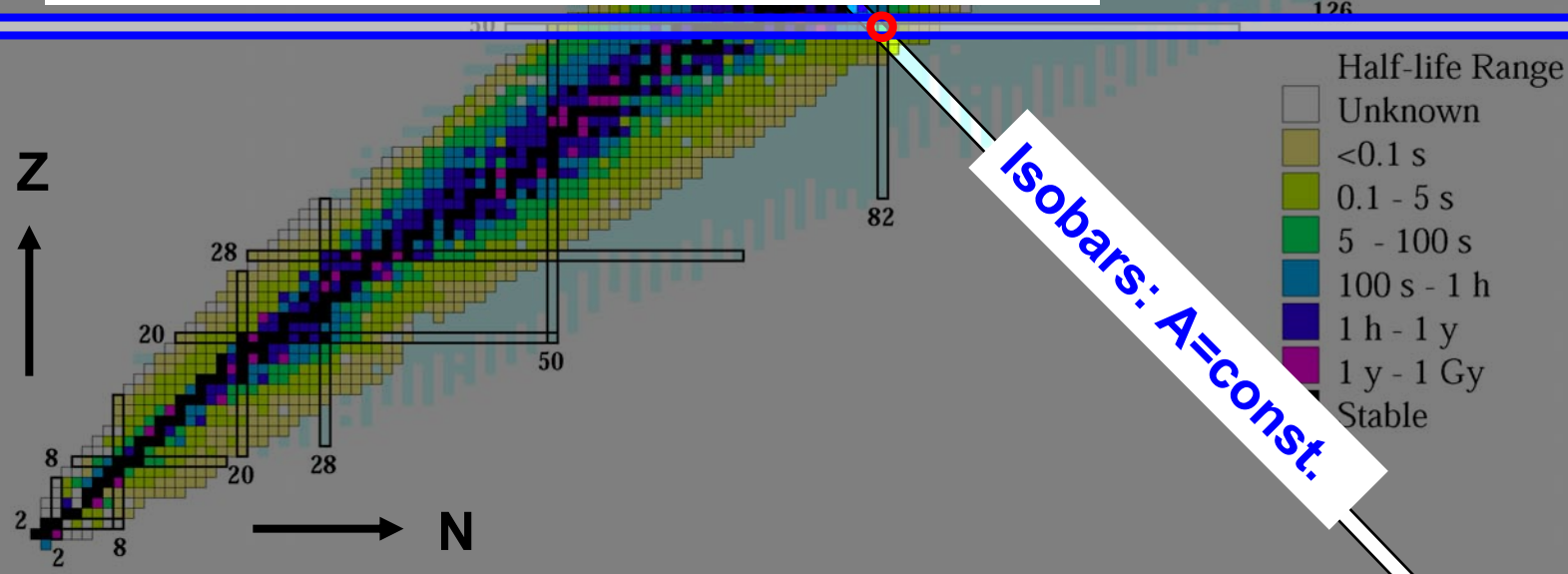
Isotope selection

- Ionisation to $q = 1+$
- Acceleration to 60 keV
- Mass selection by magnetic deflection
- $B\rho = p/q \propto \sqrt{A}$

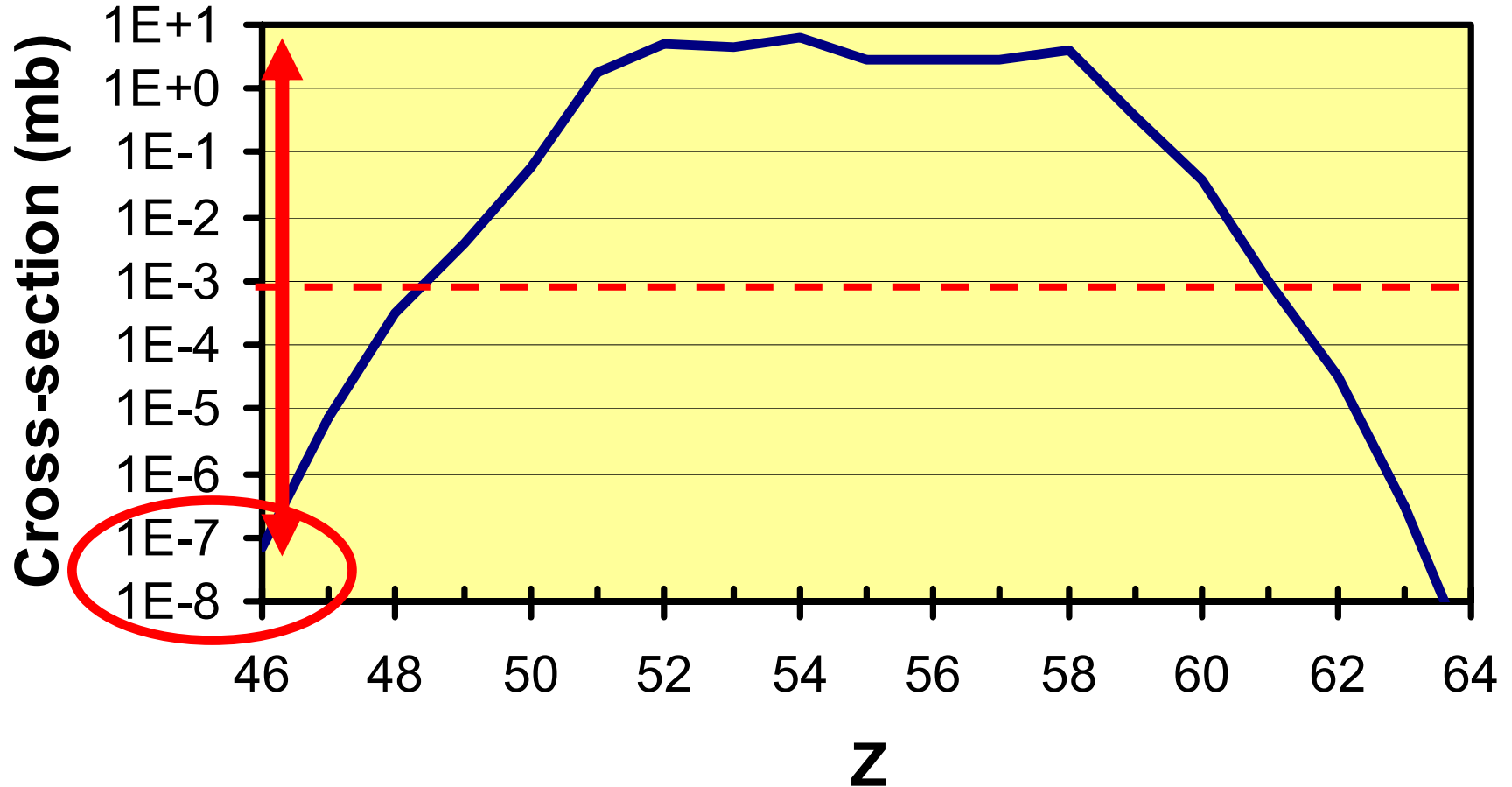
ISOLDE
CERN



Z selection by chemically selective step



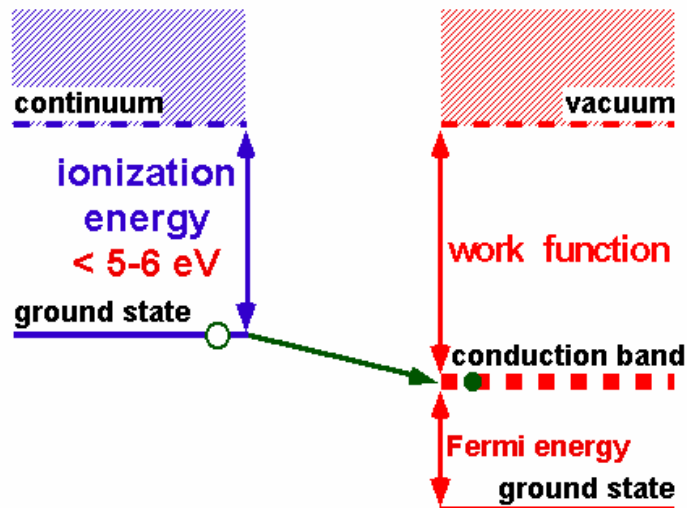
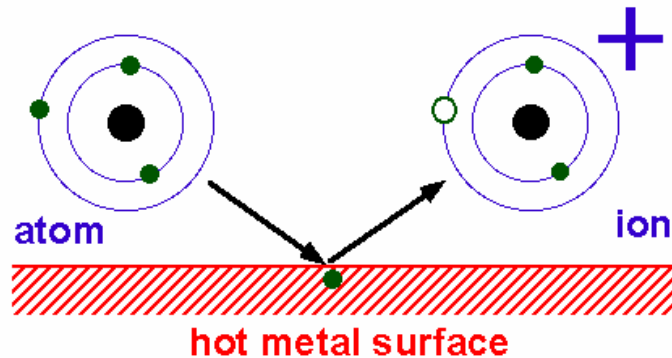
The challenge of the extremes!



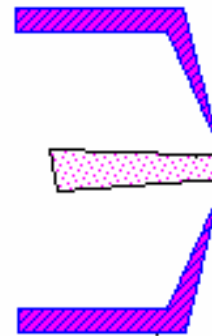
1. low cross-sections \Rightarrow optimize efficiency
2. enormous production of isobars \Rightarrow optimize selectivity
3. short half-lives \Rightarrow optimize rapidity

Positive surface ionization source

Surface Ionization

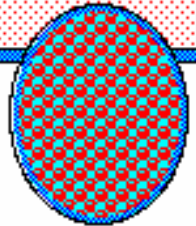


Extraction
electrode



Ta Transfer line

W Surface
ionizer



Target

$$\alpha_s = g_+/g_0 \exp(-(IP - \Phi)/kT)$$

$$\varepsilon_s = \alpha_s / (1 + \alpha_s)$$

Saha-Langmuir equation

ε_s surface ionization efficiency

Φ work function of surface

IP ionization potential of atom

$g=2J+1$ stat. factor ($g_0=2$, $g_+=1$ for alkalis)

Ionization potentials of the elements

Ionization potential: < 5 eV																					
Ionization potential: 5.0 - 5.8 eV																					
Ionization potential: 5.8 - 6.5 eV																					
1 H																2 He					
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne				
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar				
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112										

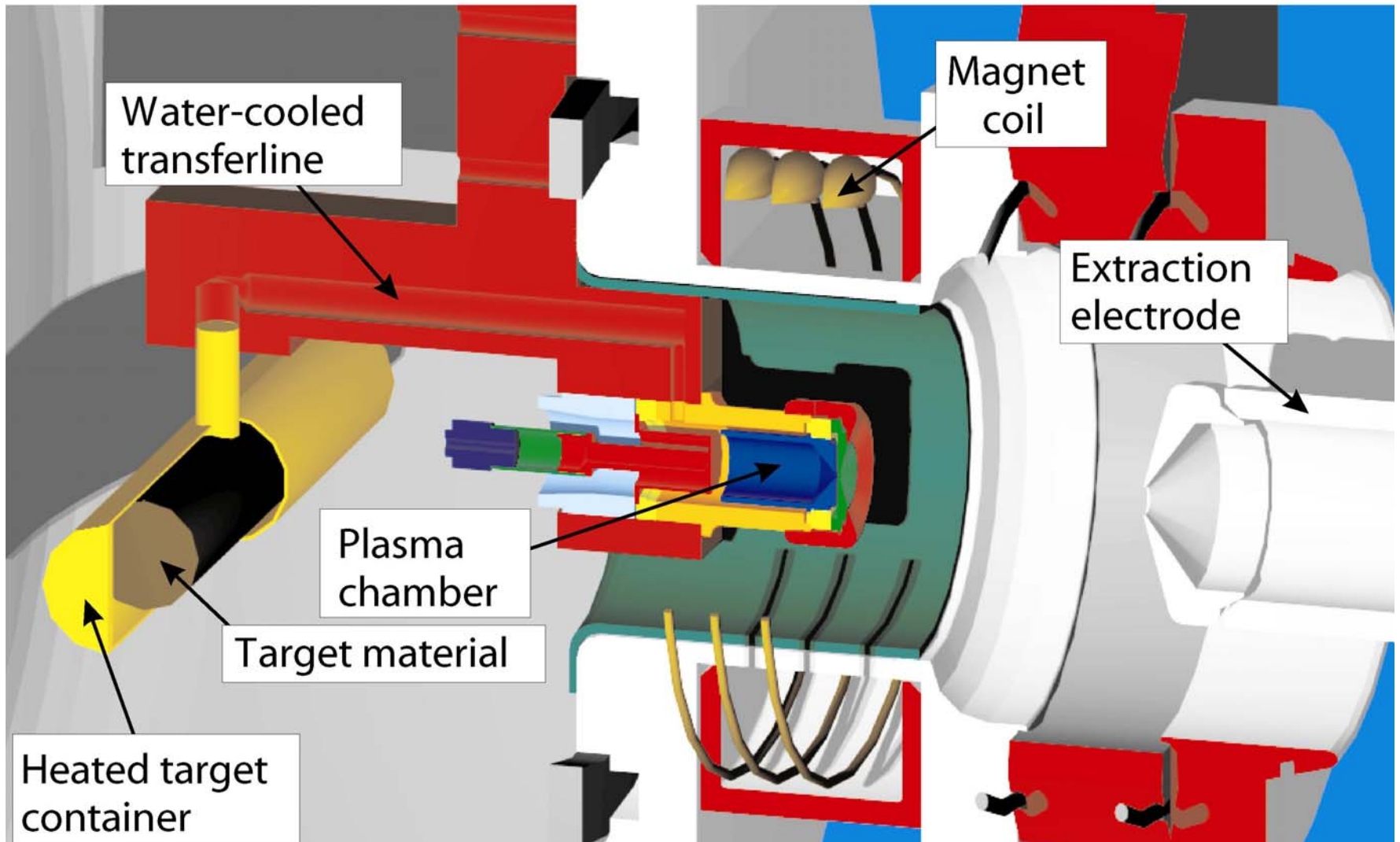
58	59	60	61	62	63	64	65	66	67	68	69	70	71
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
90	91	92	93	94	95	96	97	98	99	100	101	102	103
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Volatility of the elements

1	T (p vapor > 0.01 mbar) < 100 °C																2						
H	T (p vapor > 0.01 mbar) < 400 °C																He						
3	4	T (p vapor > 0.01 mbar) < 1000 °C																5	6	7	8	9	10
Li	Be	T (p vapor > 0.01 mbar) < 2000 °C																B	C	N	O	F	Ne
11	12	T (p vapor > 0.01 mbar) > 2000 °C																13	14	15	16	17	18
Na	Mg																	Al	Si	P	S	Cl	Ar
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36						
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr						
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54						
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe						
55	56	57	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86						
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn						
87	88	89	104	105	106	107	108	109	110	111	112												
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt															

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

ISOLDE target and ion source unit

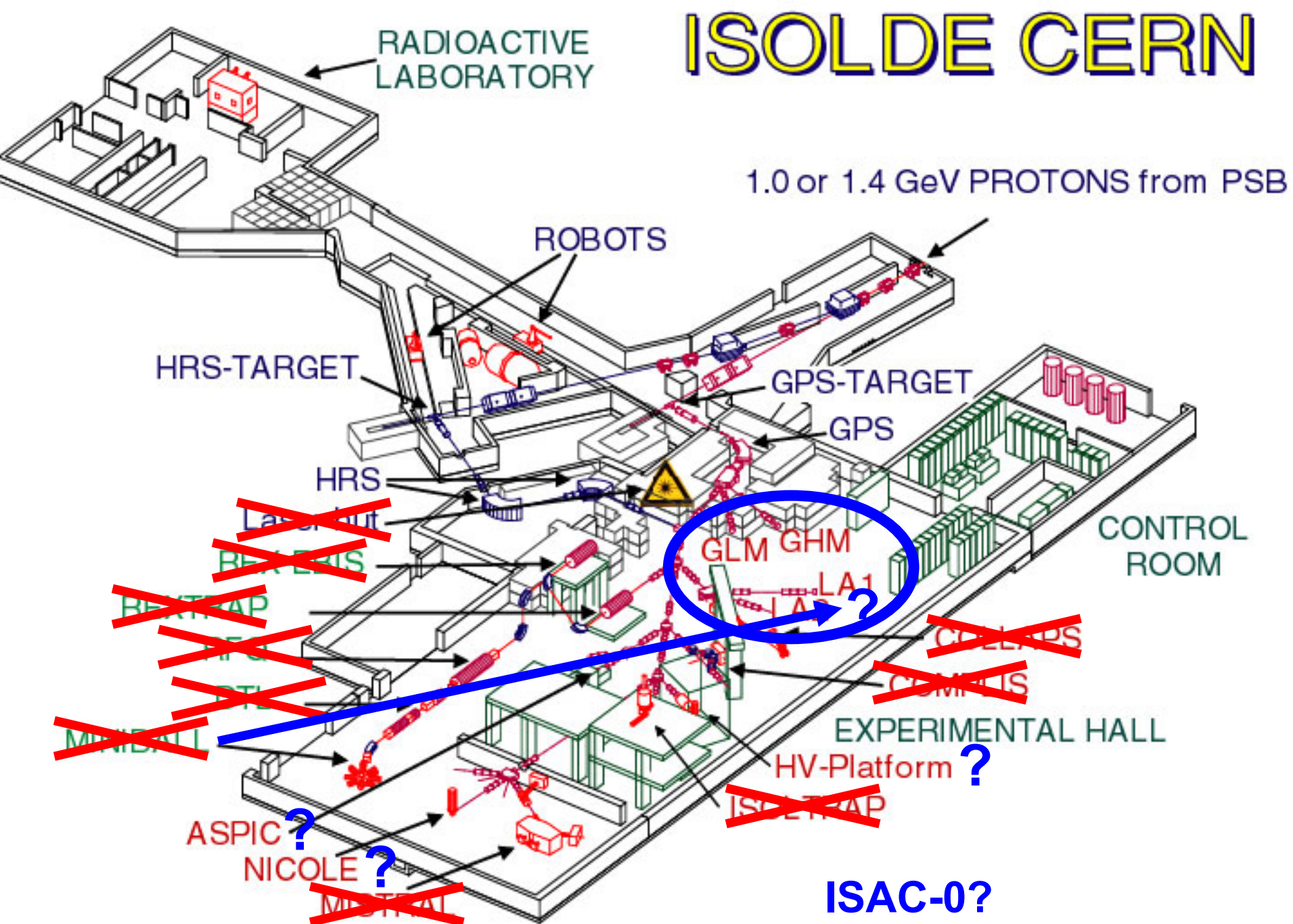


“Pure” ISOL beams without RILIS

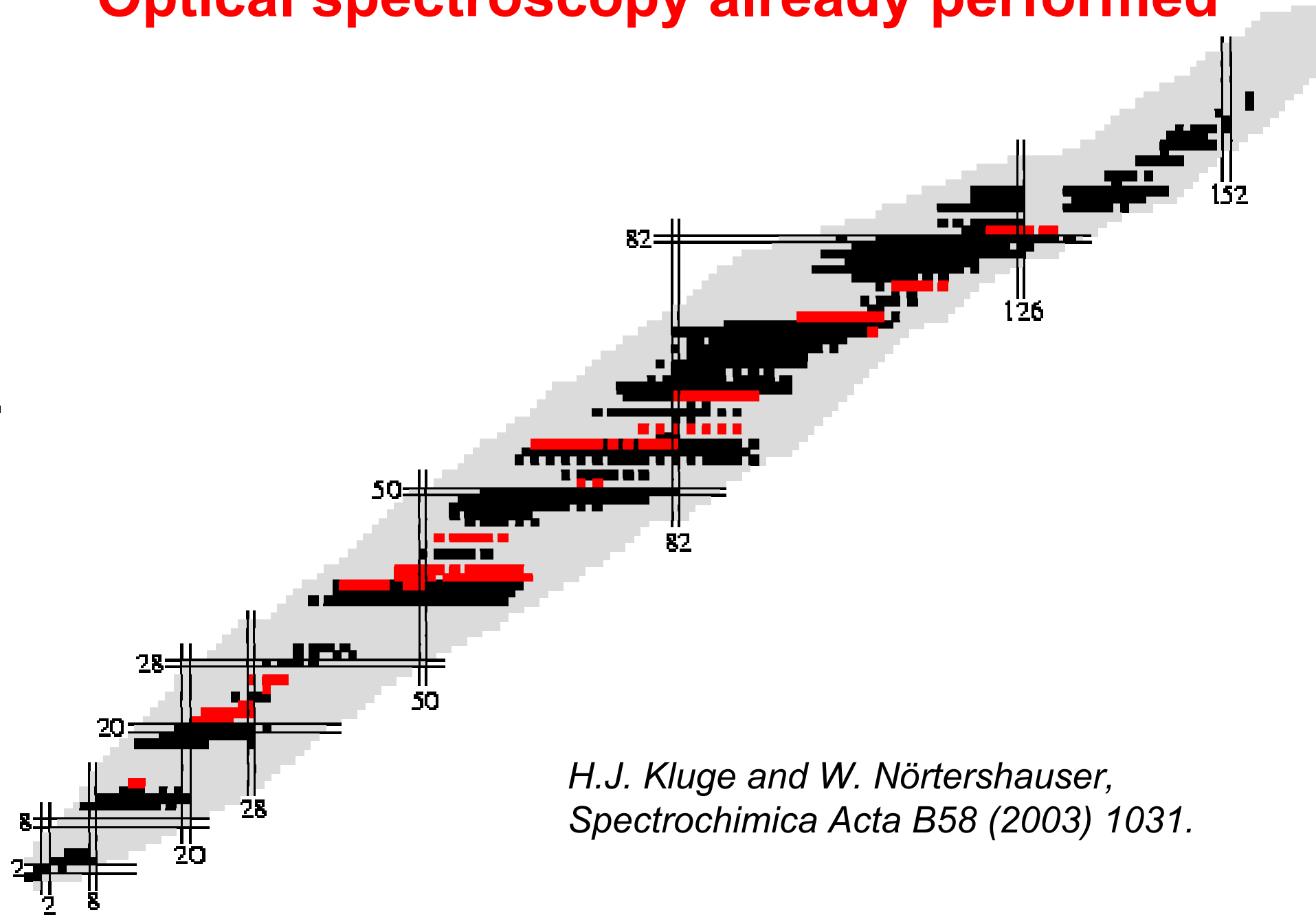
<div>Surface ionization</div> <div>Water-cooled transfer line</div> <div>Warm transfer line</div> <div>Molecular sidebands</div>																<div>n-deficient</div> <div>n-rich</div>																	
1 H																		2 He															
3 Li	4 Be																	5 B	6 C	7 N	8 O	9 F	10 Ne										
11 Na	12 Mg																	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar										
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87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112	113	114	115	116		118																

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

ISOLDE CERN



Optical spectroscopy already performed

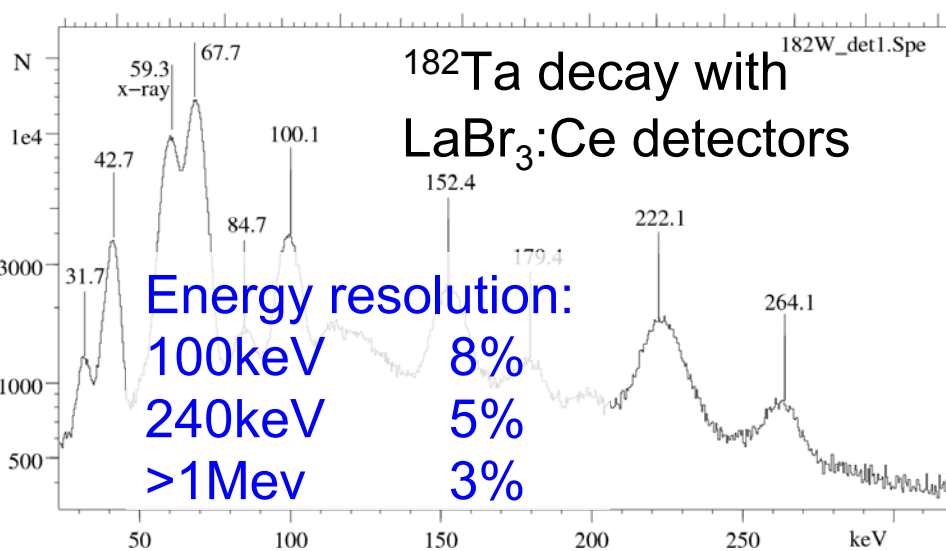


*H.J. Kluge and W. Nörtershauser,
Spectrochimica Acta B58 (2003) 1031.*

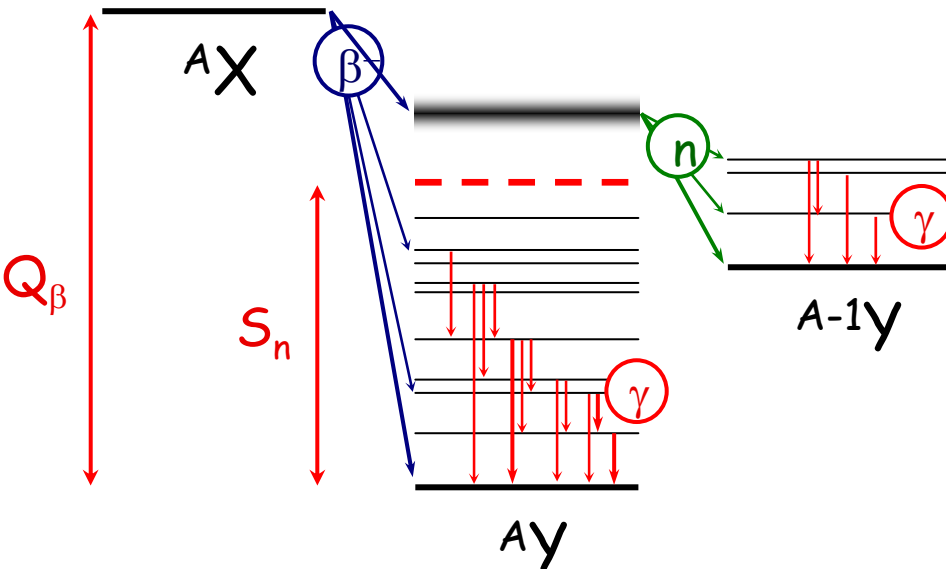
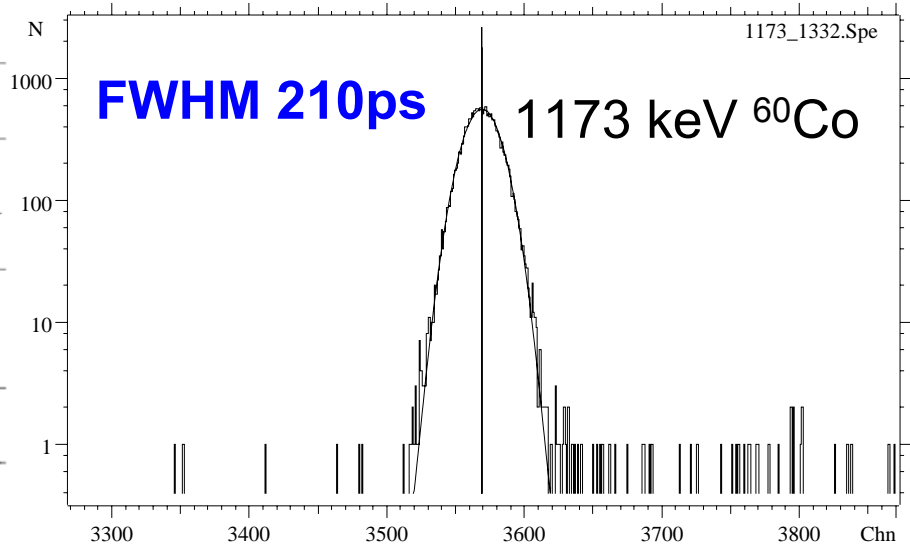
Applications in nuclear spectroscopy

- **most exotic isotopes reachable for few elements only**
- **applications with limited count rate capability or detection methods with high intrinsic selectivity but low efficiency compensated by longer running times:**
 - **fast timing measurements**
 - **E0 transitions with (mini-)orange spectrometer**
 - **beta-delayed neutron spectroscopy with TOF**
 - **superallowed Fermi decays**
 - **crystal spectrometer?**
 - **...**

New and revived nuclear spectroscopy techniques



J.M. Regis et al. (IKP Cologne, ILL)

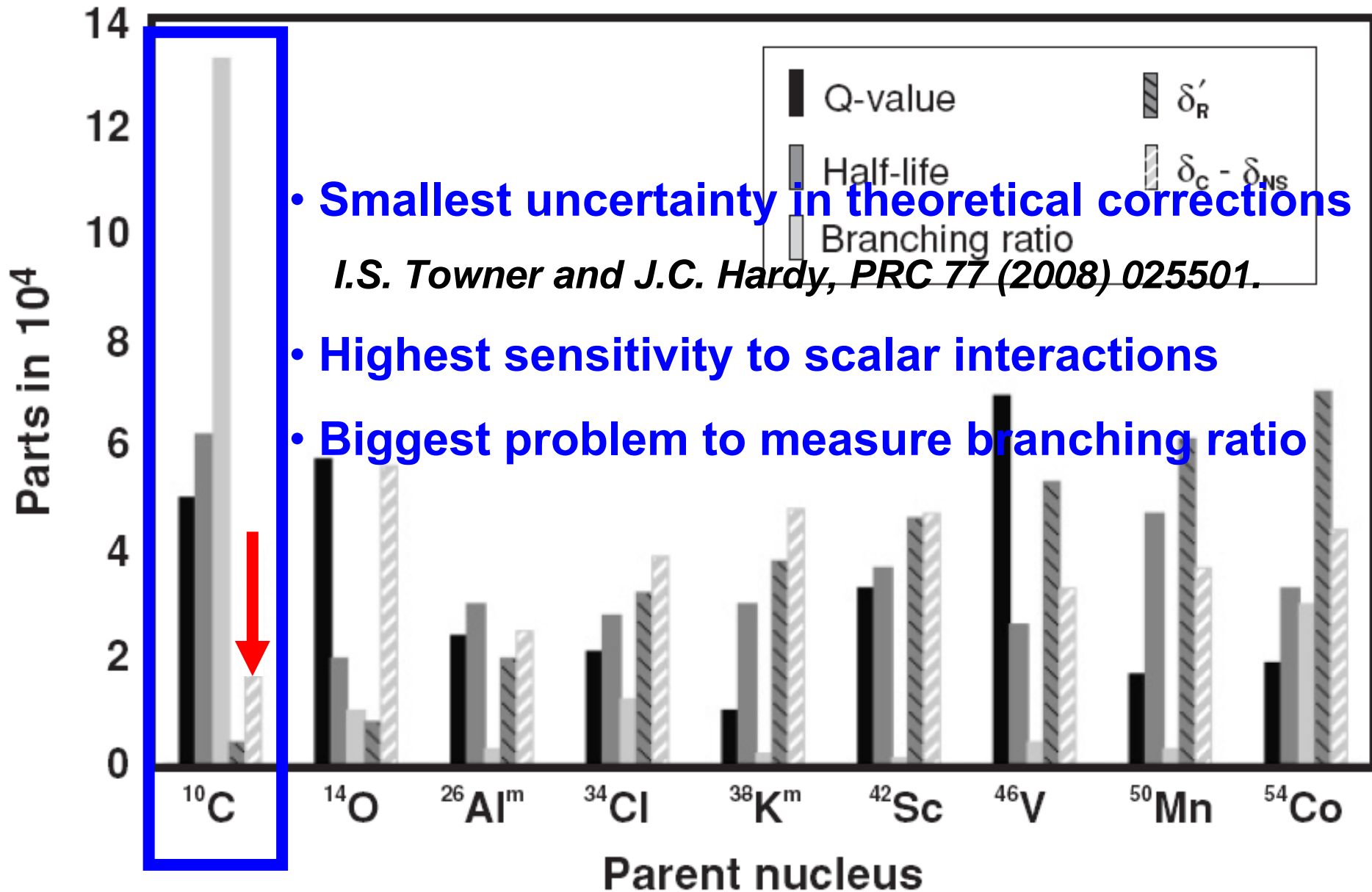


W. Schwerdtfeger et al. (LMU Munich)

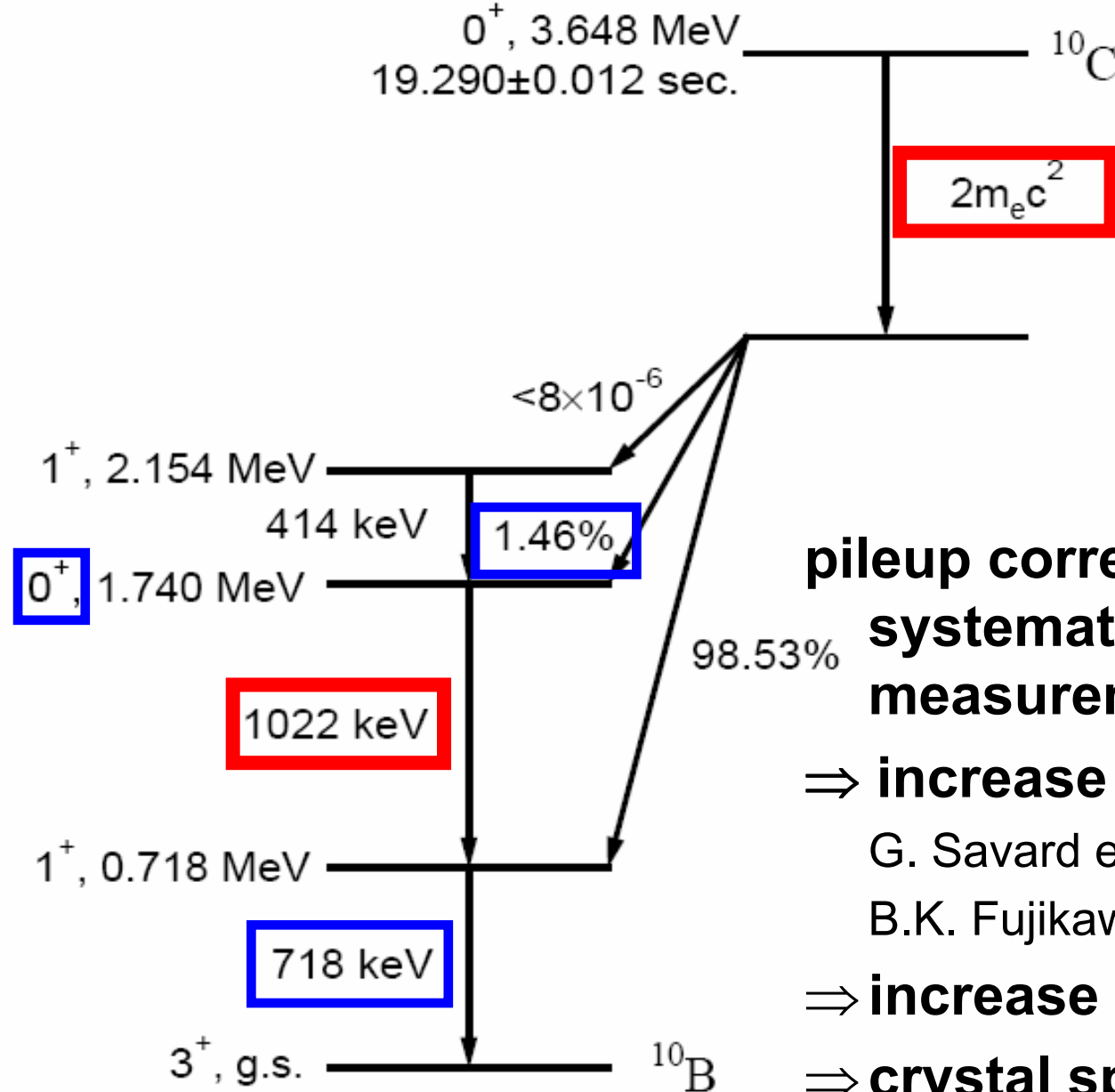
Available ISOL beams for $0^+ \rightarrow 0^+$ decay studies

- ^{10}C : **5E5/s** as CO, CaO+MK7, ISOLDE@2 uA
- ^{14}O : **4E5/s** as CO, SiC+MK11, ISAC@75 uA
- ^{18}Ne : **1E6/s**, CaO+MK7, ISOLDE@2 uA or **8E6/s**, SiC+MK11, ISAC@75 uA
- $^{26\text{m}}\text{Al}$: **4E5/s**, SiC+Re SI, ISAC@70uA
- ^{34}Ar : **3E6/s**, CaO+MK7, ISOLDE@2uA
- $^{38\text{m}}\text{K}$: **7E7/s**, TiC+Re SI, ISAC@40uA
- ^{38}Ca : **6E3/s** as CaF^+ , Ti+W SI, ISOLDE@2uA
- ^{62}Ga : **1E4/s**, ZrC+**TRILIS**, ISAC@35 uA
- ^{74}Rb : **1E4/s**, Nb+Re SI, ISAC@10 uA
- ^{98}In : **<<1/s** with present target technology

Status of superallowed Fermi decay



Branching ratio measurement in ^{10}C decay



**pileup corrections dominate
systematic error on B.R.
measurements**

⇒ increase number of detectors

G. Savard et al., PRL 74 (1995) 1521.

B.K. Fujikawa et al., PLB449 (1999) 6.

⇒ increase experiment duration

⇒ crystal spectrometer??

Dumond Geometry: Curved Crystal Spectrometer (High Resolution with Divergent Gamma Rays)

ROWLAND circle: For each position on this circle the emitted gamma rays have the same angle to the crystal planes
 $R_R = R_C / 2$

Bent Crystal:
 $R_C = \text{distance to target}$

Virtual Image

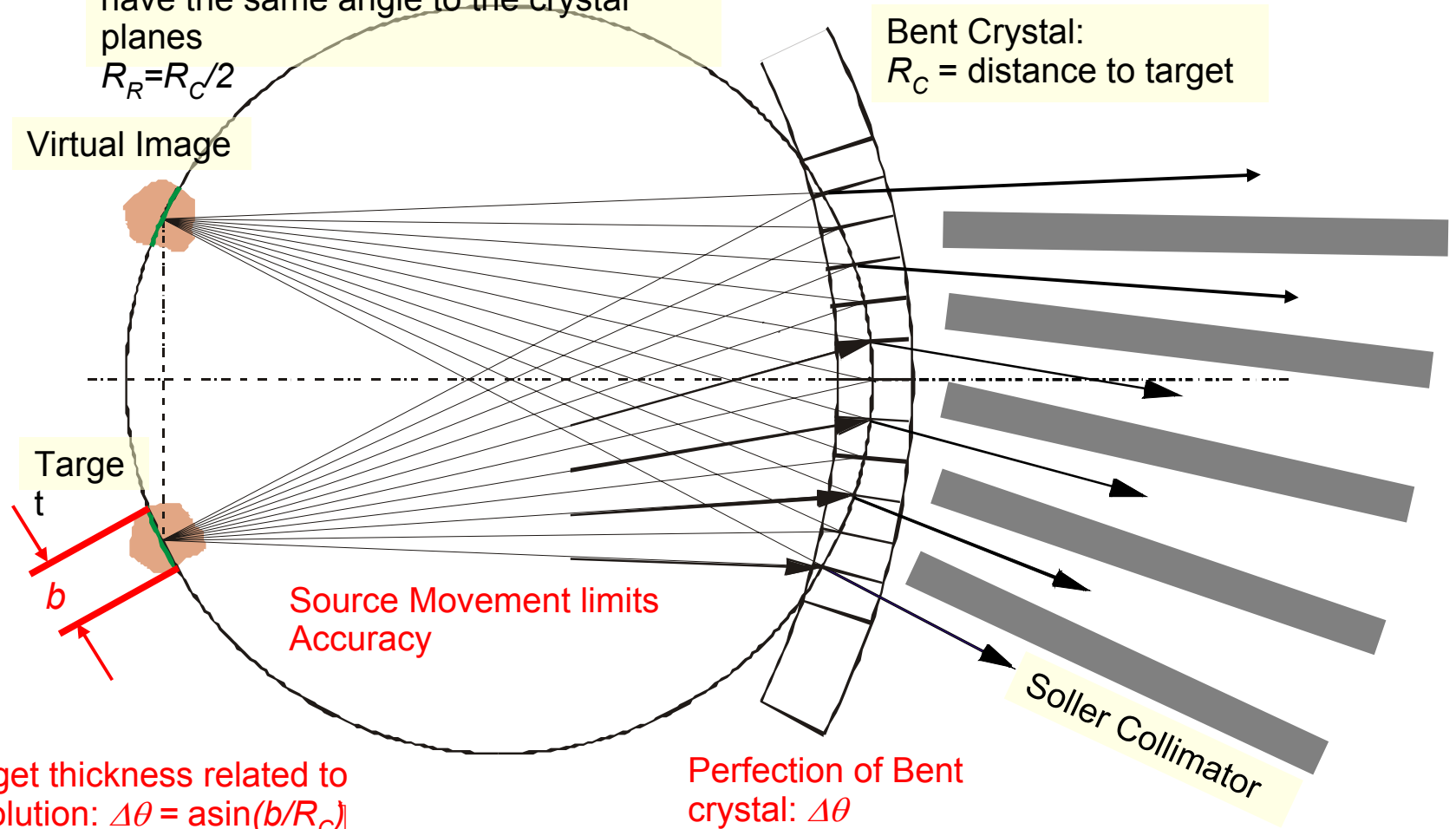
Target

Source Movement limits Accuracy

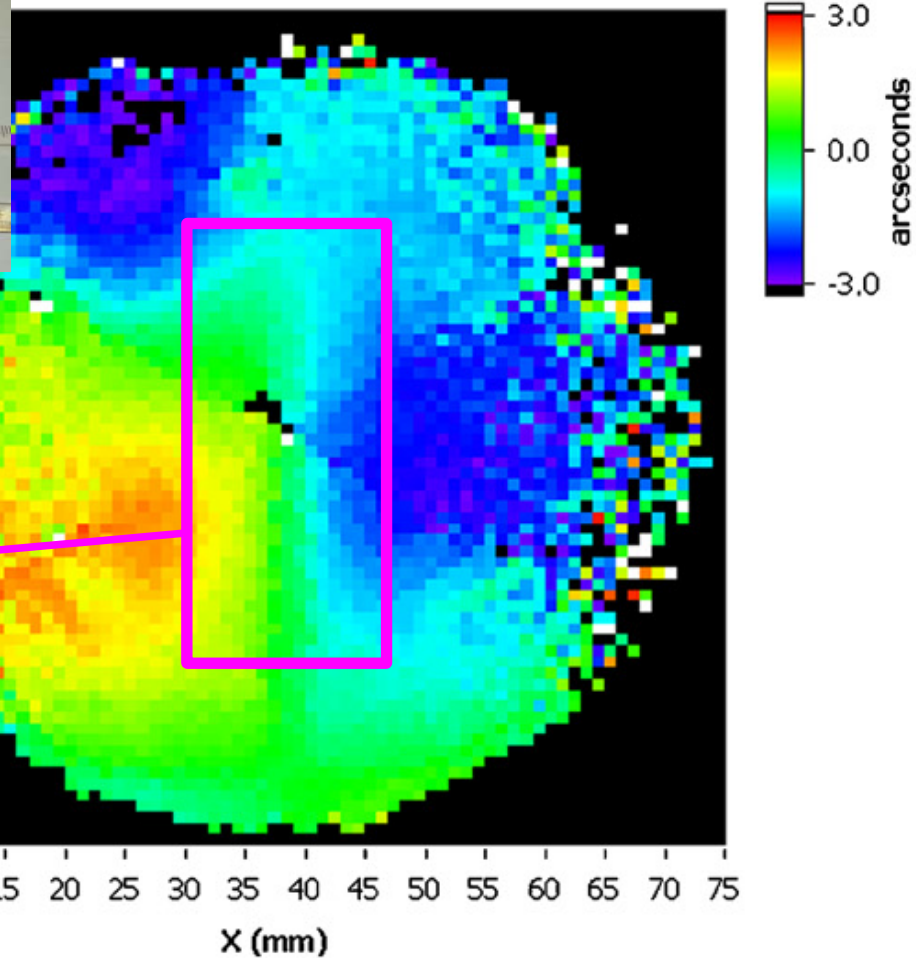
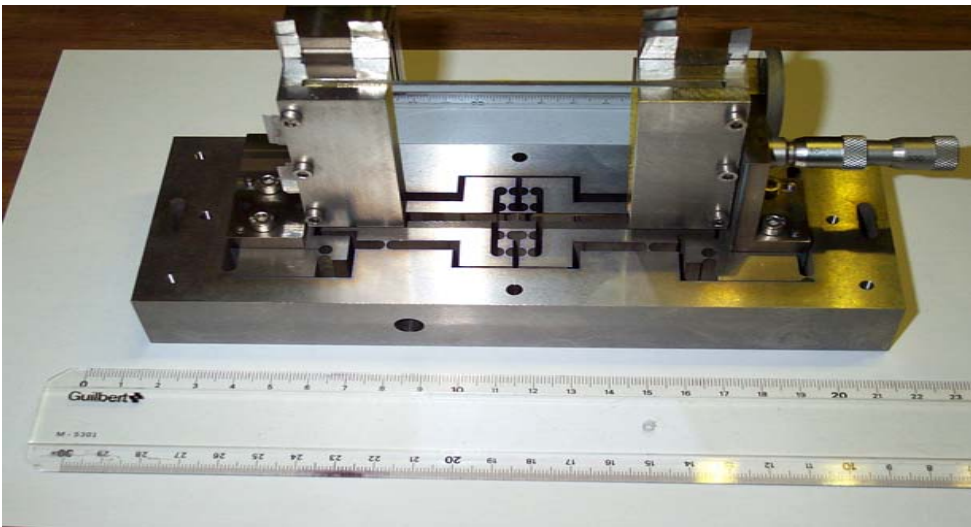
Soller Collimator

Target thickness related to resolution: $\Delta\theta = \arcsin(b/R_C)$
 $b = R_C \sin(\Delta\theta)$

Perfection of Bent crystal: $\Delta\theta$



How perfect can we curve a crystal ?



Resolution within an area of
10 x 40 mm: 2 arcsec

Solid Angle: 10^{-7}

(b)

Resolution of a Single Crystal Spectrometer

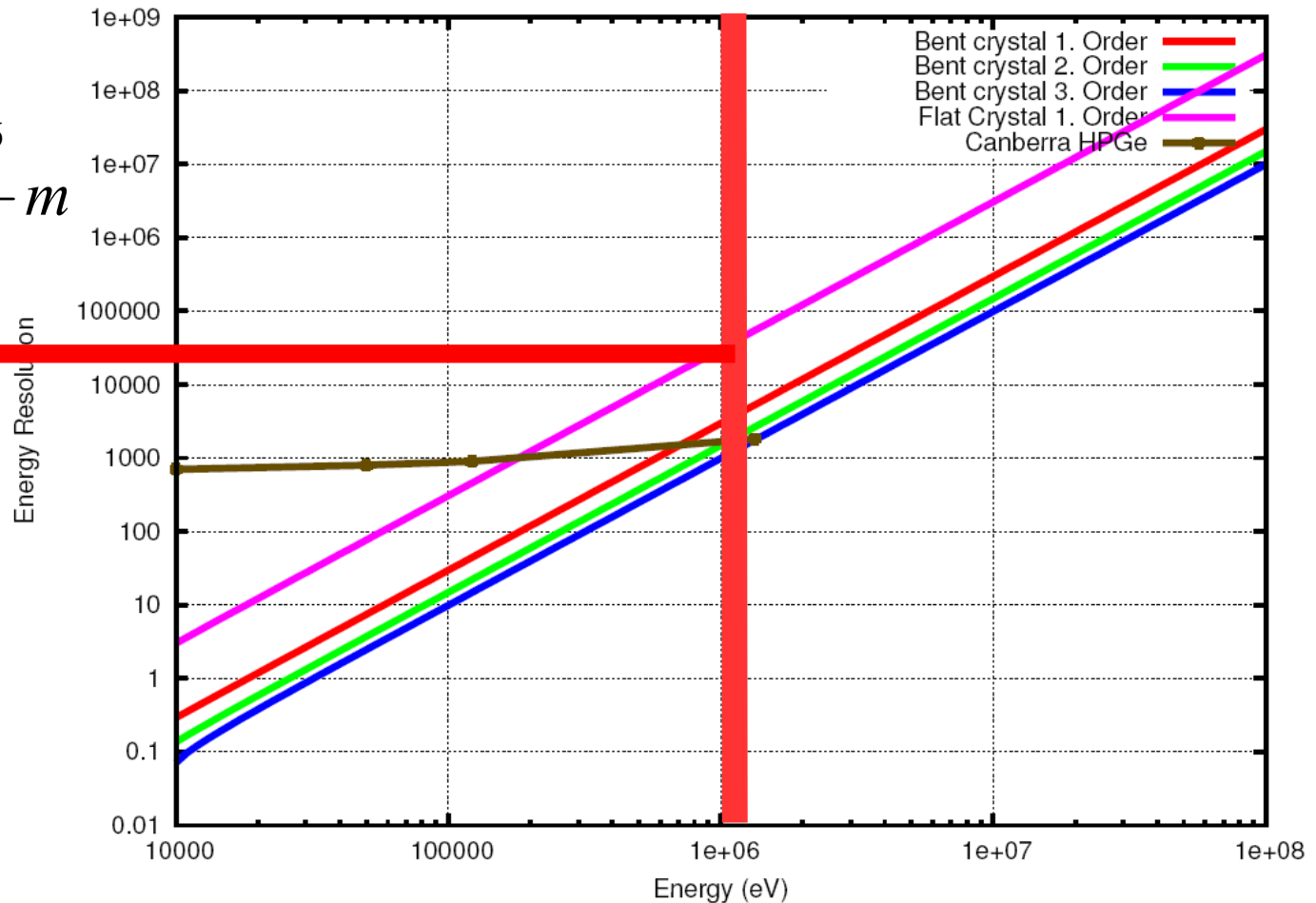
Braggs Law: $n\lambda = 2d\sin(\theta_n) \rightarrow$ Discrimination of Energies by Bragg Angles

$$d \approx 10^{-10} \text{ m}$$

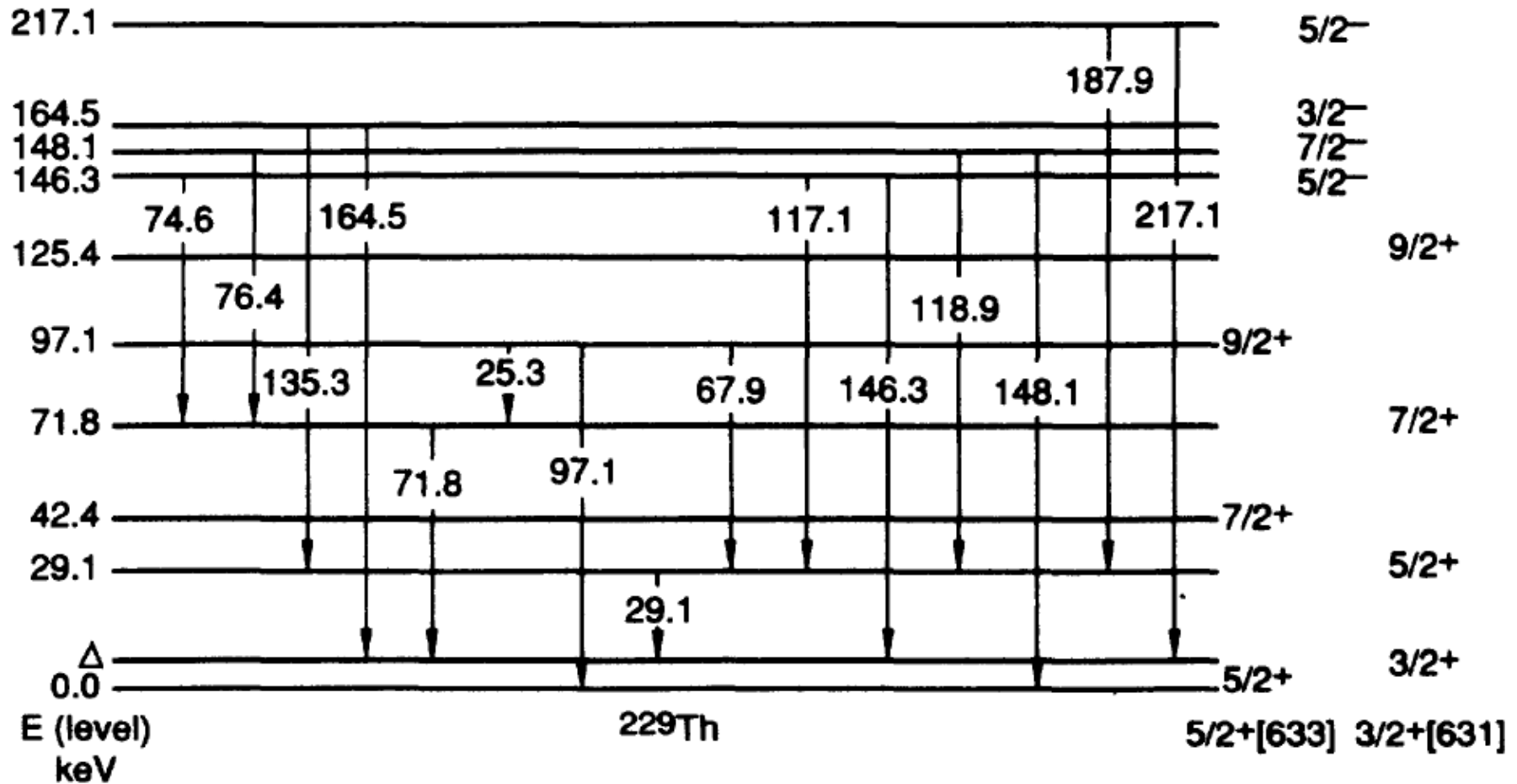
$$\lambda = \frac{h \cdot c}{E_\gamma} \cong \frac{1 \cdot 10^{-6}}{E_{[eV]}} \text{ m}$$

For $E < 1\text{MeV}$ Crystal Spectrometers have best possible Energy Resolution!

For complete Spectroscopy additional Detectors are needed!



The low-energy isomer in ^{229}Th

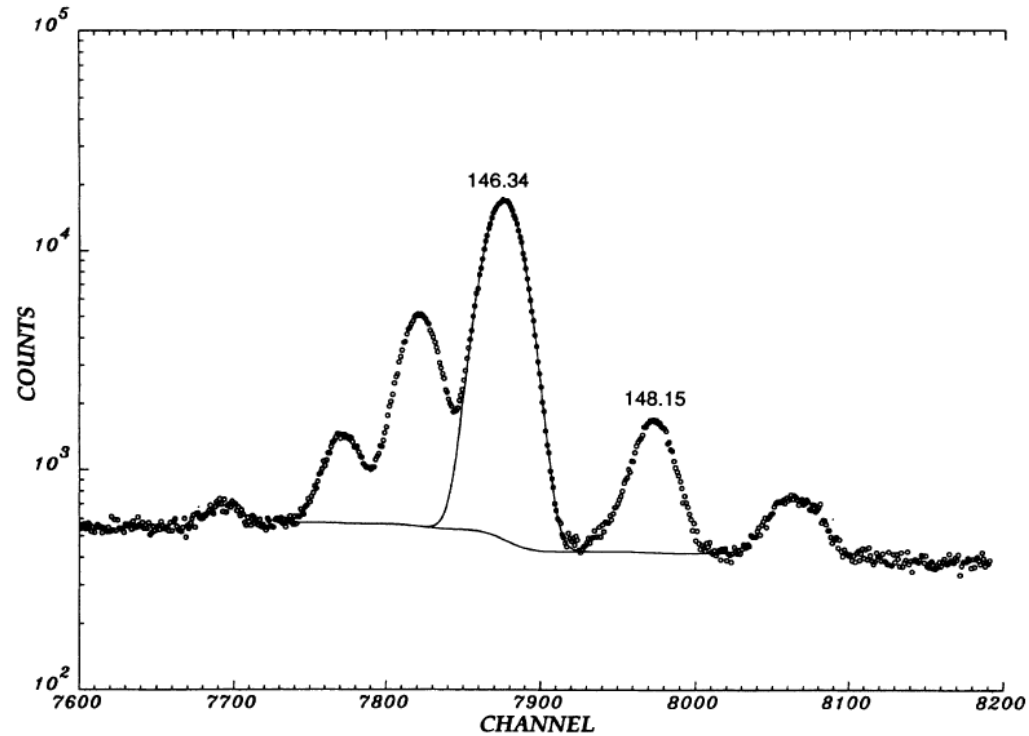
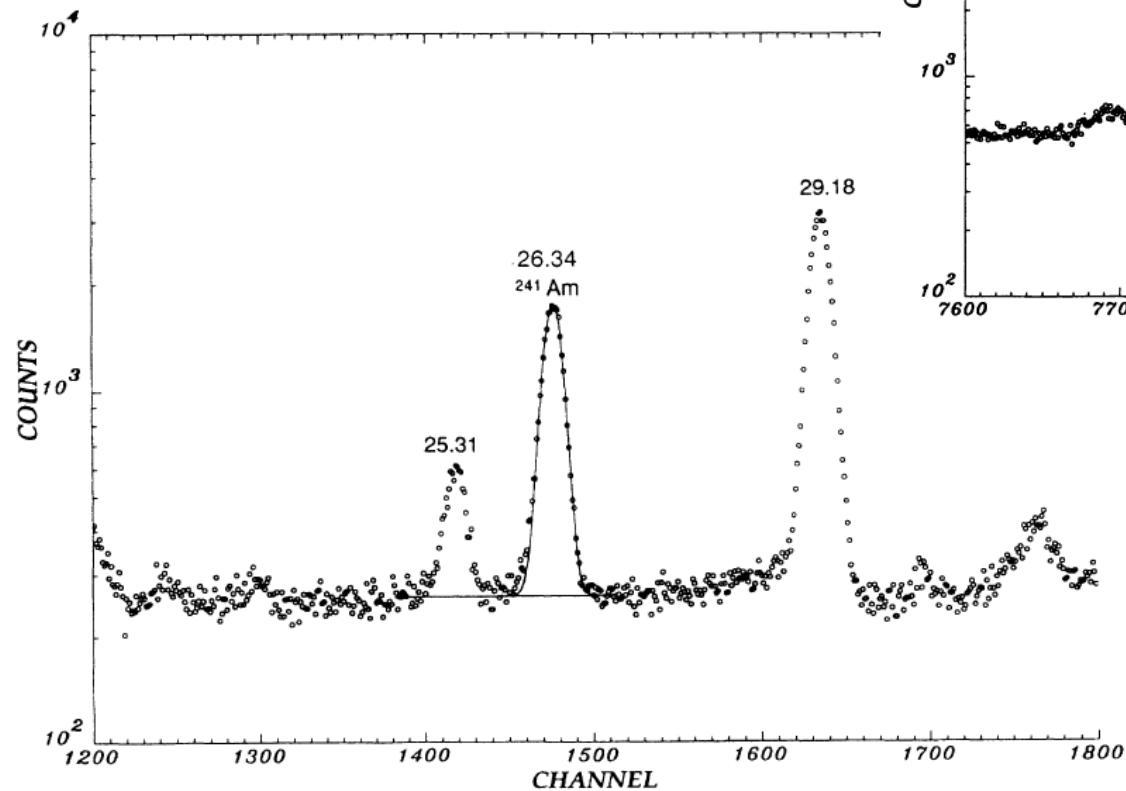


R.G. Helmer and C.G. Reich, PRC 49 (1994) 1845.

^{229m}Th measured with Ge detectors

FWHM = 270-900 eV

$\Delta = 3.5(10)$ eV



*R.G. Helmer and C.G. Reich,
PRC 49 (1994) 1845.*

$^{229\text{m}}\text{Th}$ measured with X-ray micro-calorimeter

FWHM = 26 eV

$\Delta = 7.6(5)$ eV

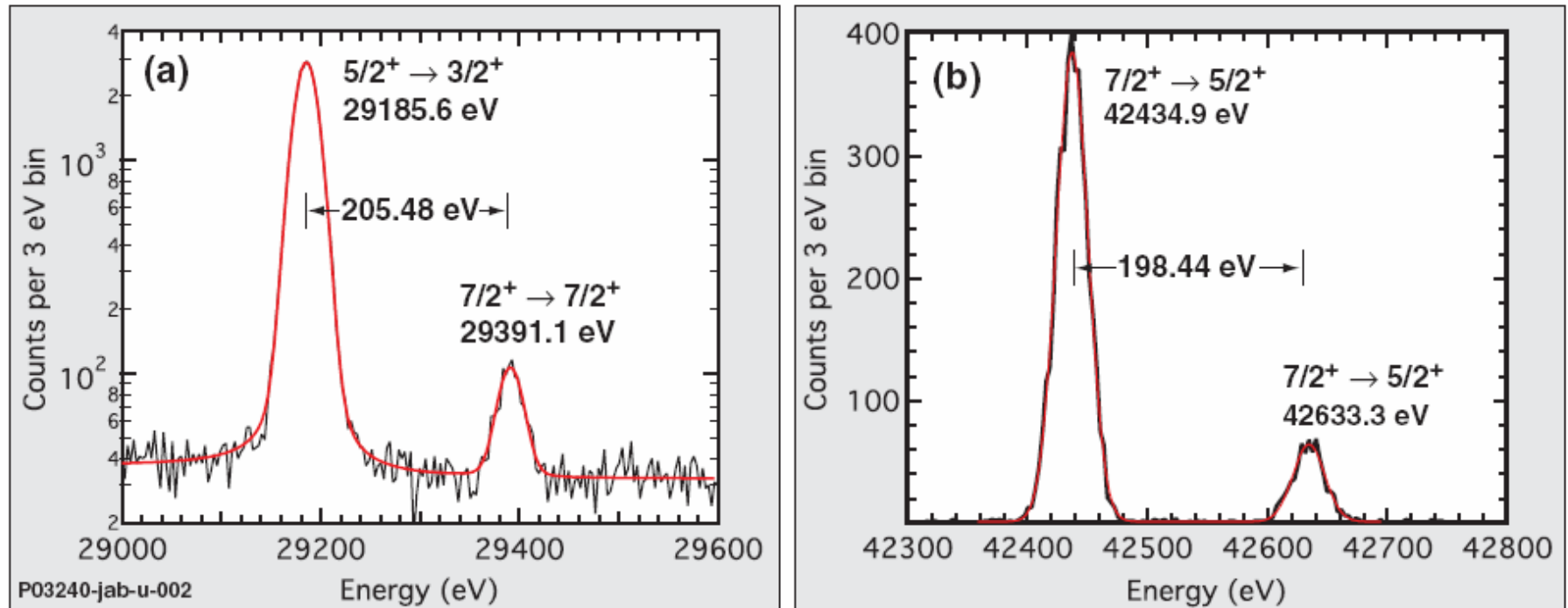


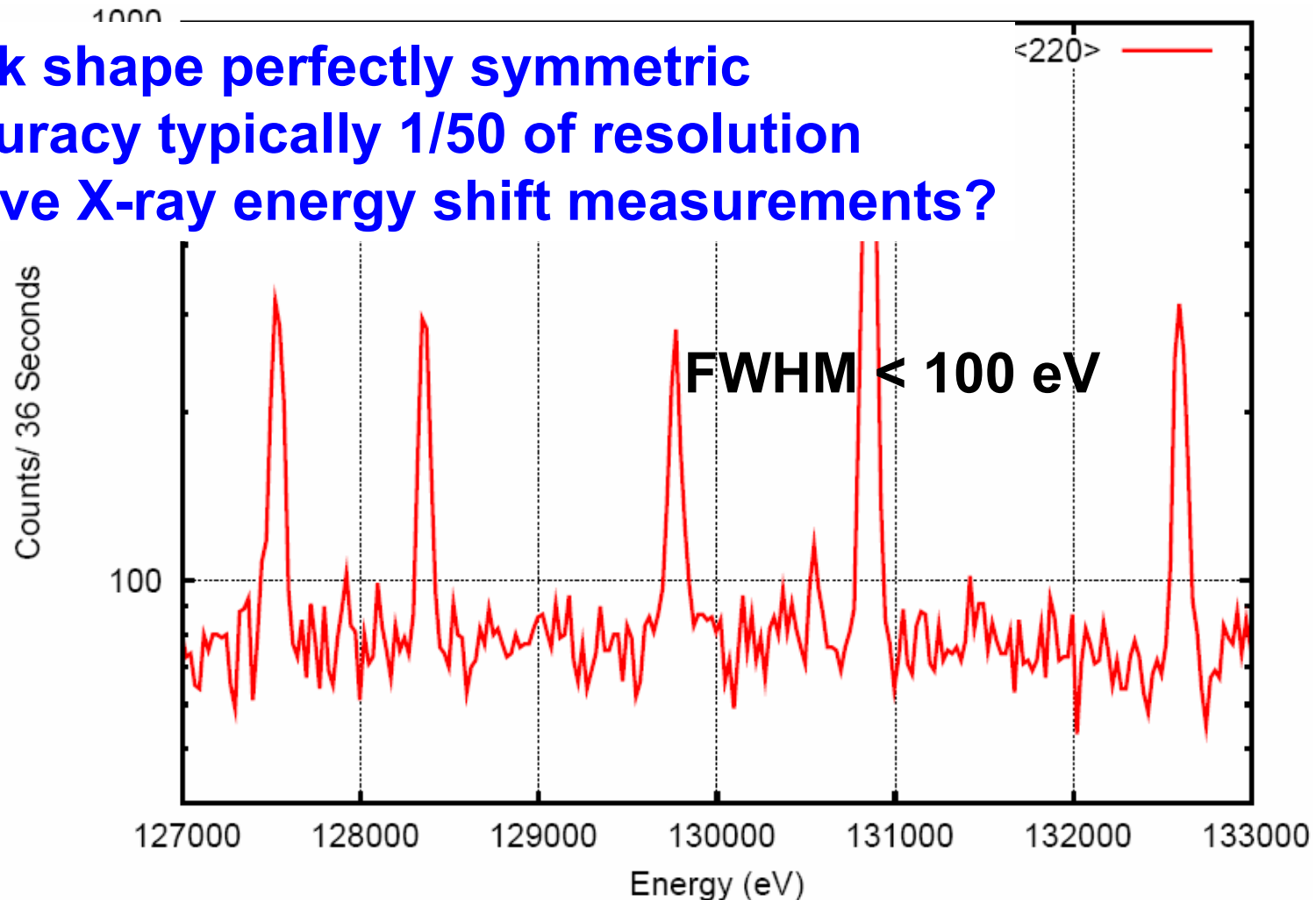
FIG. 2 (color). XRS spectra in the 29 and 42 keV energy regions. Data illustrated for the 29 keV doublet (ΔE_{29}) is the sum of 11 data sets and 25 pixels (a), and data illustrated for the 42 keV doublet (ΔE_{42}) represents the sum of 11 data sets only for pixel 0 (b). Black lines represent the data; red lines represent the least-square fitting results. Full-energy peaks are labeled by J^π of the corresponding $^{229\text{m}}\text{Th}$ transition.

B.R. Beck et al., PRL 98 (2007) 142501.

Measure $^{229\text{m}}\text{Th}$ with bent crystal spectrometer

FWHM = 1-20 eV (third order)

- peak shape perfectly symmetric
- accuracy typically 1/50 of resolution
- revive X-ray energy shift measurements?



EDM Probes of New CP Violation

f	d_{SM}	d_{exp}	d_{future}
e^-	Yale, Indiana, Amherst $< 10^{-30}$	$< 1.0 \times 10^{-27}$	$\rightarrow 10^{-31}$
n	ILL, PSI, SNS, ... $< 10^{-33}$	$< 1.0 \times 10^{-26}$	$\rightarrow 10^{-29}$
^{199}Hg	TRIUMF, KVI, ANL, Princeton... $< 10^{-33}$	$< 1.0 \times 10^{-28}$	$\rightarrow 10^{-32}$
μ	TRIUMF, KVI, ANL, Princeton... $< 10^{-33}$	$< 1.0 \times 10^{-28}$	$\rightarrow 10^{-24}$

Also ^{225}Ra , ^{129}Xe , d ← BNL

About half a dozen neutron EDM experiments under operation or preparation!

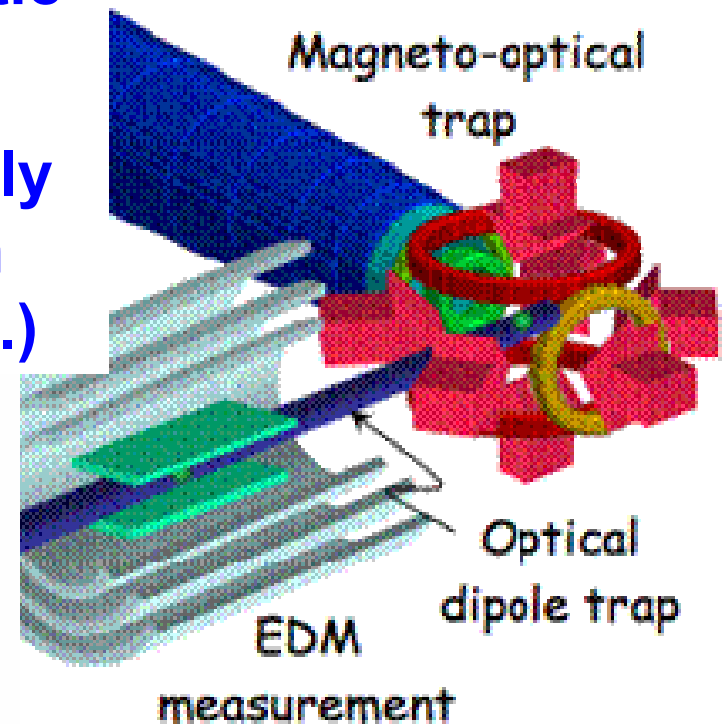
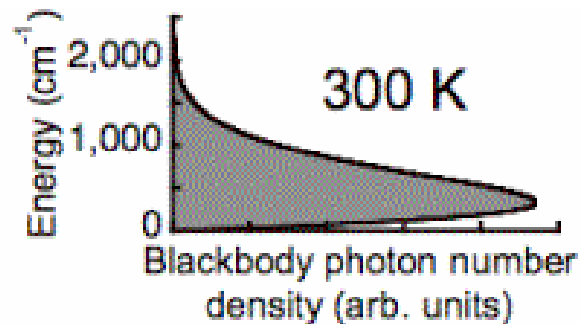
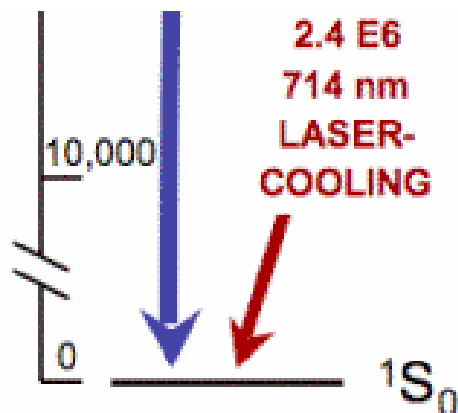
MOT

Precision experiments with neutral atom traps:

- have intrinsically low efficiency
- require long time to optimize all components and minimize systematic uncertainties
- use elements that coincide perfectly with those provided by “simple” ion sources (alkali metals, noble gases..)

J.R. Guest et al.,

PRL 98 (2007) 093001.



Cancer

About 1 000 000 new cancer cases per year in EU
58 % local disease, 42 % generalized
45 % cured (5 year survival)
22 % surgery alone
12 % radiation therapy
6 % combination surgery + radiation
5 % chemo-therapy
just beginning of systemic radionuclide therapy

HOW: expose cancer cells or cancer tissue to sufficient radiation doses?

ISOTOPES in Therapy =

surgery with radiation

	Gamma Knife	β -Knife	α -Knife	Auger Knife
ISOTOPE	^{60}Co $E_\gamma > 1 \text{ MeV}$	^{131}I , ^{90}Y , ^{153}Sm , ^{166}Ho , Others $E_\beta 1 - 3 \text{ MeV}$	$^{212}, ^{213}\text{Bi}$, ^{211}At , ^{149}Tb , $^{223}, ^{224}\text{Ra}$ $E_\alpha 4-8 \text{ MeV}$	^{125}I ^{165}Er $E_e \text{ few eV}$
Range	Full body penetration	about 1 cm	30 – 80 μm	1 μm
Application	Brain cancer,..	Radio-immuno therapy: Lymphoma..	Leukemia, Lymphoma, metastases	future
	Tissue surgery ex vivo	Tissue surgery in vivo	Cell surgery	Molecular surgery

Cancer therapy with alpha emitters

- half-life
- radiotoxicity of daughter isotopes
- biokinetics: in-vivo stability of chelating agent, clearance,...
- affordable
- reliable supply: more than one facility per geographic area

GBq activity/patient sufficient!

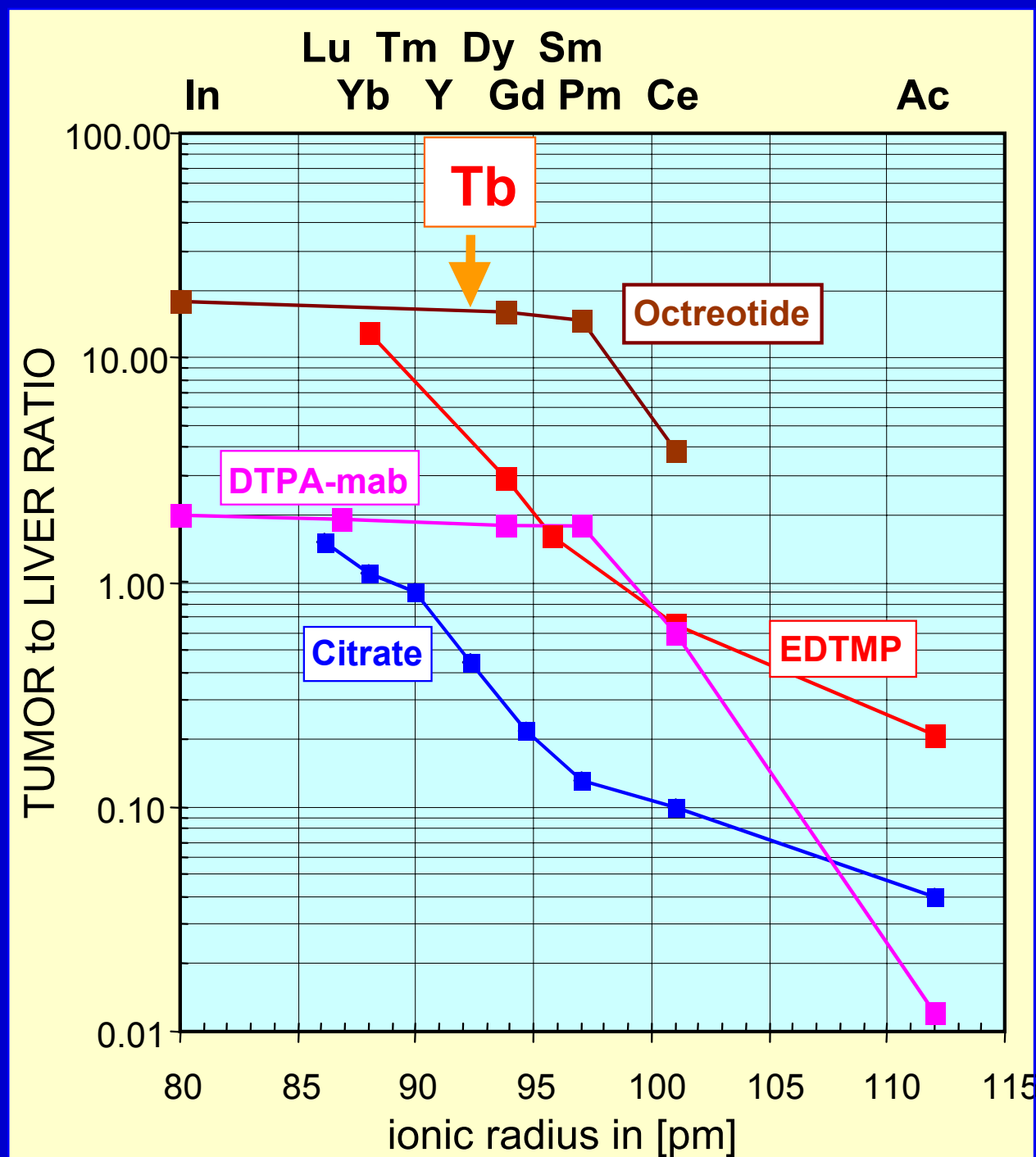


Isotopes for targeted alpha therapy

Ac 213 0.80 s	Ac 214 8.2 s	Ac 215 0.17 s	Ac 216 0.44 ms	Ac 217 0.74 μs	Ac 218 1.1 μs	Ac 219 11.8 μs	Ac 220 26 ms	Ac 221 52 ms	Ac 222 63 s	Ac 223 2.10 m	Ac 224 2.9 h	Ac 225 10.0 d	Ac 226 29 h
α 7.36	α 7.215; 7.081... γ 139; 244...	α 7.600; 7.211... γ (396...)	α 9.029; 9.105... γ 83; 854; 771...	α 9.50; 495; 352... γ 10.54... α 9.85	α 9.205 g	α 8.664	α 7.85; 7.61; 7.68... γ 134...	α 7.65; 7.44; 7.38...	α 6.81; 6.75; 6.69; 7.06... γ 7... g	α 7.009; 6.564...; ε γ (99; 191; 84...)	α 6.142; 6.060; 6.214... γ 100; 150; 198... C 14	α 5.830; 5.790; 5.732...; C 14 γ 100; 150; 230; 156; 254; 186...	β ⁻ 0.9; 1.1 ε; α 5.34 γ 230; 156; 254; 186...
Ra 212 13.0 s	Ra 213 2.1 ms	Ra 214 2.46 s	Ra 215 1.67 ms	Ra 216 2.0 ns	Ra 217 1.6 μs	Ra 218 25.6 μs	Ra 219 10 ms	Ra 220 23 ms	Ra 221 28 s	Ra 222 38 s	Ra 223 11.43 d	Ra 224 3.66 d	Ra 225 14.8 d
α 6.899... γ (535)	α 6.824; 1003; 161...; ε γ (535)	α 7.137; 6.505 ε; g γ (642)	α 8.700; 7.879... γ 834; 540	α 8.700; 7.879... γ 834; 540	α 8.99 g	α 8.99 g	α 7.679; 7.989... γ 316; 214; 592...	α 7.46... γ 465	α 6.613; 6.761; 6.668... γ 149; 93; 174... C 14	α 6.559; 6.237 γ 324; (329; 473...) C 14	α 5.7162; 5.6067; γ 269; 154; 324... C 14; α 130; γ 241...; C 14 α <0.7	α 5.6854; 5.4486... γ 241...; C 14 α <0.7	β ⁻ 0.3; 0.4 γ 40 ε
Fr 211 3.10 m	Fr 212 20.0 m	Fr 213 34.6 s	Fr 214 3.35 ms	Fr 215 0.09 μs	Fr 216 0.70 μs	Fr 217 16 μs	Fr 218 22 ms	Fr 219 21 ms	Fr 220 27.4 s	Fr 221 4.9 m	Fr 222 14.2 m	Fr 223 21.8 m	Fr 224 3.3 m
α 6.535 γ 540; 918; 281...	α 6.262; 6.354; 6.406; 6.340... γ 1274; 227; 1165...	α 6.775	α 6.477; 8.547...	α 8.426; 8.336...	α 9.36	α 9.01 g	α 7.815; 7.580; 7.555... h	α 7.867; 7.576... h	α 6.68; 6.63; 6.58... β ⁻ ... γ 45; 106; 162...	α 6.341; 6.126... γ 218; (101; 411...) C 14	β ⁻ 1.8... γ 206; 211; 242... α ?	β ⁻ 1.1... α 5.34 γ 50; 90; 235...	β ⁻ 2.6; 2.6... γ 216; 132; 837; 1341...
Rn 210 2.4 h	Rn 211 14.6 h	Rn 212 24 m	Rn 213 19.5 ms	Rn 214 6.5 ns	Rn 215 2.3 μs	Rn 216 45 μs	Rn 217 0.54 ms	Rn 218 35 ms	Rn 219 3.96 s	Rn 220 55.6 s	Rn 221 25 m	Rn 222 3.825 d	Rn 223 23.2 m
α 6.040... γ 458; (571); 649; 73...	α 5.783; 5.851... γ 674; 1363; 678...; g	α 6.264...	α 8.068; 7.252... γ 540	α 10.63; 10.46... γ 10.63; 10.46... γ 10.63; 10.46...	α 8.67 g	α 8.05 g	α 7.133... γ (809)	α 6.819; 6.553; 6.425... γ 271; 402...	α 6.288... γ (550) σ <0.2	β ⁻ 0.8; 1.1... α 6.037; 5.798; 5.778 γ 198; 150...	α 5.48948... γ (510) σ 0.74	α 5.48948... γ (510) σ 0.74	β ⁻ ... γ 593; 417; 636; 655...
At 209 5.4 h	At 210 8.3 h	At 211 7.22 h	At 212 119 ms	At 213 0.11 μs	At 214 0.76 μs	At 215 0.1 ms	At 216 0.3 ms	At 217 32.3 ms	At 218 ~2 s	At 219 0.9 m	At 220 3.71 m	At 221 2.3 m	At 222 54 s
α 5.647 γ 545; 782; 790...	α 5.524; 5.442; 5.361... γ 1161; 245; 1483...	α 5.857... γ (887...) g	α 7.84; 7.80... γ 83... ε	α 7.86; 7.82... γ 83... ε	α 8.819 γ	α 8.026... γ (405)	α 7.804; 7.691...; g γ (116); 418...	α 7.069... β ⁻ ... γ (259; 334; 589...)	α 6.694; 6.653... β ⁻ ... γ	α 6.27 β ⁻	β ⁻ ... α 5.493 γ 241; 293; 422...	β ⁻ ... γ	β ⁻ ...
Po 208 2.898 a	Po 209 102 a	Po 210 138.38 d	Po 211 25.2 s	Po 212 45.1 ns	Po 213 4.2 μs	Po 214 164 μs	Po 215 1.78 ms	Po 216 0.15 s	Po 217 1.53 s	Po 218 3.05 m	Po 219 >300 ns	Po 220 >300 ns	
α 5.1152... γ (292; 571...) g	α 4.881... γ (895; 261; 263...)	α 5.30438... γ (803); σ <0.0005 γ (895; 261; 263...)	α 7.275; 6.862... γ 370; 1064... γ 370; 1064...	α 7.452... γ 370; 1064... γ 370; 1064...	α 8.376... γ (270)	α 7.6889... γ (800; 336)	α 7.3682... β ⁻ ... γ (439...)	α 6.7783... γ (805)	α 6.543 β ⁻	α 6.0024... γ	β ⁻ ? α ?	β ⁻ ?	
Bi 207 31.55 a	Bi 208 3.68 · 10 ⁵ a	Bi 209 100	Bi 210 5.013 d	Bi 211 2.17 m	Bi 212 25 m	Bi 213 45.59 m	Bi 214 19.9 m	Bi 215 36.9 s	Bi 216 3.6 m	Bi 217 98.5 s	Bi 218 33 s	136	
α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 0.011 ± 0.023 γ α <3E-7	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615	α 5.494; 4.998... γ 356; 304... γ 2615
Pb 206 24.1	Pb 207 22.1	Pb 208 52.4	Pb 209 3.253 h	Pb 210 22.3 a	Pb 211 36.1 m	Pb 212 10.64 h	Pb 213 10.2 m	Pb 214 26.8 m	134		132		
α 0.027	α 0.61	α 0.00023 γ α <8E-6	β ⁻ 0.6 no γ	β ⁻ 0.02; 0.06 γ 47; α ?; g α 3.72 α <0.5	β ⁻ 1.4... γ 405; 632; 427...	β ⁻ 0.3; 0.6... γ 239; 300... g	β ⁻ 0.7; 1.0... γ 352; 295; 242...	β ⁻ 0.7; 1.0... γ 352; 295; 242...	134		132		
Tl 205 70.48	Tl 206 3.7 m	Tl 207 4.77 m	Tl 208 3.053 m	Tl 209 2.16 m	Tl 210 1.30 m	Tl 211 >300 ns	Tl 212 >300 ns	134		132			
α 0.11	α 0.11	α 0.11	α 0.11	α 0.11	α 0.11	α 0.11	α 0.11	134		132			

^{149}Tb for targeted alpha therapy

Er 148 4.6 s α 1312, 244; 155, 610... β^- 1171, 1095; 1030, 910...	Er 149 18.5 s α 839; 1171, 1095; 1030, 910...	Er 150 18.5 s α 2.8; 1171, 1095; 1030, 910...	Er 151 20.3 s α 937; 1171, 1095; 1030, 910...	Er 152 10.3 s α 4.30; 1171, 1095; 1030, 910...	Er 153 37.1 s α 4.67; 1171, 1095; 1030, 910...	Er 154 3.73 m α 4.17; 1171, 1095; 1030, 910...	Er 155 5.3 m α 4.02; 1171, 1095; 1030, 910...	Er 156 18.6 m α 3.8; 1171, 1095; 1030, 910...	Er 157 18.65 m α 3.7; 1171, 1095; 1030, 910...	Er 158 2.25 h α 3.6; 1171, 1095; 1030, 910...	Er 159 36 m α 3.5; 1171, 1095; 1030, 910...	Er 160 26.6 h α 3.4; 1171, 1095; 1030, 910...	Er 161 3.24 h α 3.3; 1171, 1095; 1030, 910...	Er 162 0.139 α 3.2; 1171, 1095; 1030, 910...	Er 163 75 m α 3.1; 1171, 1095; 1030, 910...	Er 164 1.801 α 3.0; 1171, 1095; 1030, 910...
Ho 147 5.8 s α 139, 284; 487, 1364; 1030, 910...	Ho 148 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 149 21 s α 139, 284; 487, 1364; 1030, 910...	Ho 150 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 151 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 152 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 153 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 154 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 155 48 m α 139, 284; 487, 1364; 1030, 910...	Ho 156 73 m α 139, 284; 487, 1364; 1030, 910...	Ho 157 12.6 m α 139, 284; 487, 1364; 1030, 910...	Ho 158 21 m α 139, 284; 487, 1364; 1030, 910...	Ho 159 21 m α 139, 284; 487, 1364; 1030, 910...	Ho 160 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 161 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 162 32 s α 139, 284; 487, 1364; 1030, 910...	Ho 163 1.1 s α 139, 284; 487, 1364; 1030, 910...
Dy 146 29 s α 139, 284; 487, 1364; 1030, 910...	Dy 147 32 s α 139, 284; 487, 1364; 1030, 910...	Dy 148 3.1 m α 139, 284; 487, 1364; 1030, 910...	Dy 149 4.2 m α 139, 284; 487, 1364; 1030, 910...	Dy 150 7.2 m α 139, 284; 487, 1364; 1030, 910...	Dy 151 17 m α 139, 284; 487, 1364; 1030, 910...	Dy 152 2.4 h α 139, 284; 487, 1364; 1030, 910...	Dy 153 6.29 h α 139, 284; 487, 1364; 1030, 910...	Dy 154 3.0 $\cdot 10^4$ a α 139, 284; 487, 1364; 1030, 910...	Dy 155 10.0 h α 139, 284; 487, 1364; 1030, 910...	Dy 156 0.056 α 139, 284; 487, 1364; 1030, 910...	Dy 157 8.1 h α 139, 284; 487, 1364; 1030, 910...	Dy 158 0.095 α 139, 284; 487, 1364; 1030, 910...	Dy 159 144.4 d α 139, 284; 487, 1364; 1030, 910...	Dy 160 2.329 α 139, 284; 487, 1364; 1030, 910...	Dy 161 18.889 α 139, 284; 487, 1364; 1030, 910...	Dy 162 25.475 α 139, 284; 487, 1364; 1030, 910...
Tb 145 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 146 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 147 1.83 h α 139, 284; 487, 1364; 1030, 910...	Tb 148 22 m α 139, 284; 487, 1364; 1030, 910...	Tb 149 4.2 m α 139, 284; 487, 1364; 1030, 910...	Tb 150 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 151 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 152 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 153 2.34 d α 139, 284; 487, 1364; 1030, 910...	Tb 154 32 s α 139, 284; 487, 1364; 1030, 910...	Tb 155 5.32 d α 139, 284; 487, 1364; 1030, 910...	Tb 156 24 s α 139, 284; 487, 1364; 1030, 910...	Tb 157 39 s α 139, 284; 487, 1364; 1030, 910...	Tb 158 15 s α 139, 284; 487, 1364; 1030, 910...	Tb 159 100 α 139, 284; 487, 1364; 1030, 910...	Tb 160 72.3 d α 139, 284; 487, 1364; 1030, 910...	Tb 161 6.90 d α 139, 284; 487, 1364; 1030, 910...
Gd 144 4.5 m α 139, 284; 487, 1364; 1030, 910...	Gd 145 32 s α 139, 284; 487, 1364; 1030, 910...	Gd 146 48.3 d α 139, 284; 487, 1364; 1030, 910...	Gd 147 38.1 h α 139, 284; 487, 1364; 1030, 910...	Gd 148 74.6 s α 139, 284; 487, 1364; 1030, 910...	Gd 149 9.28 d α 139, 284; 487, 1364; 1030, 910...	Gd 150 1.8 $\cdot 10^4$ a α 139, 284; 487, 1364; 1030, 910...	Gd 151 120 d α 139, 284; 487, 1364; 1030, 910...	Gd 152 0.20 α 139, 284; 487, 1364; 1030, 910...	Gd 153 239.47 d α 139, 284; 487, 1364; 1030, 910...	Gd 154 2.18 α 139, 284; 487, 1364; 1030, 910...	Gd 155 14.80 α 139, 284; 487, 1364; 1030, 910...	Gd 156 20.47 α 139, 284; 487, 1364; 1030, 910...	Gd 157 15.65 α 139, 284; 487, 1364; 1030, 910...	Gd 158 24.84 α 139, 284; 487, 1364; 1030, 910...	Gd 159 18.48 h α 139, 284; 487, 1364; 1030, 910...	Gd 160 21.85 α 139, 284; 487, 1364; 1030, 910...
Eu 143 2.6 m α 139, 284; 487, 1364; 1030, 910...	Eu 144 10.2 s α 139, 284; 487, 1364; 1030, 910...	Eu 145 5.93 d α 139, 284; 487, 1364; 1030, 910...	Eu 146 4.51 d α 139, 284; 487, 1364; 1030, 910...	Eu 147 24.6 d α 139, 284; 487, 1364; 1030, 910...	Eu 148 55.6 d α 139, 284; 487, 1364; 1030, 910...	Eu 149 93.1 d α 139, 284; 487, 1364; 1030, 910...	Eu 150 122 s α 139, 284; 487, 1364; 1030, 910...	Eu 151 47.81 α 139, 284; 487, 1364; 1030, 910...	Eu 152 32 s α 139, 284; 487, 1364; 1030, 910...	Eu 153 52.19 α 139, 284; 487, 1364; 1030, 910...	Eu 154 48.0 m α 139, 284; 487, 1364; 1030, 910...	Eu 155 4.761 a α 139, 284; 487, 1364; 1030, 910...	Eu 156 15.2 d α 139, 284; 487, 1364; 1030, 910...	Eu 157 15.18 h α 139, 284; 487, 1364; 1030, 910...	Eu 158 46 m α 139, 284; 487, 1364; 1030, 910...	Eu 159 18.1 m α 139, 284; 487, 1364; 1030, 910...
Sm 142 72.4 m α 139, 284; 487, 1364; 1030, 910...	Sm 143 32 s α 139, 284; 487, 1364; 1030, 910...	Sm 144 3.07 α 139, 284; 487, 1364; 1030, 910...	Sm 145 340 d α 139, 284; 487, 1364; 1030, 910...	Sm 146 1.03 $\cdot 10^4$ a α 139, 284; 487, 1364; 1030, 910...	Sm 147 14.99 α 139, 284; 487, 1364; 1030, 910...	Sm 148 11.24 α 139, 284; 487, 1364; 1030, 910...	Sm 149 13.82 α 139, 284; 487, 1364; 1030, 910...	Sm 150 7.38 α 139, 284; 487, 1364; 1030, 910...	Sm 151 93 a α 139, 284; 487, 1364; 1030, 910...	Sm 152 26.75 α 139, 284; 487, 1364; 1030, 910...	Sm 153 46.27 h α 139, 284; 487, 1364; 1030, 910...	Sm 154 22.75 α 139, 284; 487, 1364; 1030, 910...	Sm 155 22.4 m α 139, 284; 487, 1364; 1030, 910...	Sm 156 9.4 h α 139, 284; 487, 1364; 1030, 910...	Sm 157 8.11 m α 139, 284; 487, 1364; 1030, 910...	Sm 158 5.51 m α 139, 284; 487, 1364; 1030, 910...
Pm 141 20.9 m α 139, 284; 487, 1364; 1030, 910...	Pm 142 40.5 s α 139, 284; 487, 1364; 1030, 910...	Pm 143 265 d α 139, 284; 487, 1364; 1030, 910...	Pm 144 1.0 a α 139, 284; 487, 1364; 1030, 910...	Pm 145 17.7 a α 139, 284; 487, 1364; 1030, 910...	Pm 146 5.53 a α 139, 284; 487, 1364; 1030, 910...	Pm 147 2.62 a α 139, 284; 487, 1364; 1030, 910...	Pm 148 32 s α 139, 284; 487, 1364; 1030, 910...	Pm 149 53.1 h α 139, 284; 487, 1364; 1030, 910...	Pm 150 2.7 h α 139, 284; 487, 1364; 1030, 910...	Pm 151 28.4 h α 139, 284; 487, 1364; 1030, 910...	Pm 152 32 s α 139, 284; 487, 1364; 1030, 910...	Pm 153 5.3 m α 139, 284; 487, 1364; 1030, 910...	Pm 154 27 m α 139, 284; 487, 1364; 1030, 910...	Pm 155 41.5 s α 139, 284; 487, 1364; 1030, 910...	Pm 156 26.7 s α 139, 284; 487, 1364; 1030, 910...	Pm 157 10.6 s α 139, 284; 487, 1364; 1030, 910...
Nd 140 3.37 d α 139, 284; 487, 1364; 1030, 910...	Nd 141 32 s α 139, 284; 487, 1364; 1030, 910...	Nd 142 27.2 α 139, 284; 487, 1364; 1030, 910...	Nd 143 12.2 α 139, 284; 487, 1364; 1030, 910...	Nd 144 23.8 α 139, 284; 487, 1364; 1030, 910...	Nd 145 8.3 α 139, 284; 487, 1364; 1030, 910...	Nd 146 17.2 α 139, 284; 487, 1364; 1030, 910...	Nd 147 10.98 d α 139, 284; 487, 1364; 1030, 910...	Nd 148 5.7 α 139, 284; 487, 1364; 1030, 910...	Nd 149 1.73 h α 139, 284; 487, 1364; 1030, 910...	Nd 150 5.6 α 139, 284; 487, 1364; 1030, 910...	Nd 151 12.4 m α 139, 284; 487, 1364; 1030, 910...	Nd 152 11.4 m α 139, 284; 487, 1364; 1030, 910...	Nd 153 28.9 s α 139, 284; 487, 1364; 1030, 910...	Nd 154 25.9 s α 139, 284; 487, 1364; 1030, 910...	Nd 155 8.9 s α 139, 284; 487, 1364; 1030, 910...	Nd 156 5.5 s α 139, 284; 487, 1364; 1030, 910...
Pr 139 4.5 h α 139, 284; 487, 1364; 1030, 910...	Pr 140 3.4 m α 139, 284; 487, 1364; 1030, 910...	Pr 141 100 α 139, 284; 487, 1364; 1030, 910...	Pr 142 14.5 m α 139, 284; 487, 1364; 1030, 910...	Pr 143 13.57 d α 139, 284; 487, 1364; 1030, 910...	Pr 144 7.2 m α 139, 284; 487, 1364; 1030, 910...	Pr 145 5.98 h α 139, 284; 487, 1364; 1030, 910...	Pr 146 24.0 m α 139, 284; 487, 1364; 1030, 910...	Pr 147 13.6 m α 139, 284; 487, 1364; 1030, 910...	Pr 148 28 m α 139, 284; 487, 1364; 1030, 910...	Pr 149 2.25 m α 139, 284; 487, 1364; 1030, 910...	Pr 150 5 s α 139, 284; 487, 1364; 1030, 910...	Pr 151 18.9 s α 139, 284; 487, 1364; 1030, 910...	Pr 152 3.8 s α 139, 284; 487, 1364; 1030, 910...	Pr 153 4.3 s α 139, 284; 487, 1364; 1030, 910...	Pr 154 2.3 s α 139, 284; 487, 1364; 1030, 910...	Pr 155 >300 ns α 139, 284; 487, 1364; 1030, 910...
Ce 138 0.251 α 139, 284; 487, 1364; 1030, 910...	Ce 139 56.5 s α 139, 284; 487, 1364; 1030, 910...	Ce 140 17.8 s α 139, 284; 487, 1364; 1030, 910...	Ce 141 32.50 d α 139, 284; 487, 1364; 1030, 910...	Ce 142 11.114 α 139, 284; 487, 1364; 1030, 910...	Ce 143 33.0 h α 139, 284; 487, 1364; 1030, 910...	Ce 144 284.8 d α 139, 284; 487, 1364; 1030, 910...	Ce 145 2.98 m α 139, 284; 487, 1364; 1030, 910...	Ce 146 13.5 m α 139, 284; 487, 1364; 1030, 910...	Ce 147 57 s α 139, 284; 487, 1364; 1030, 910...	Ce 148 48 s α 139, 284; 487, 1364; 1030, 910...	Ce 149 5 s α 139, 284; 487, 1364; 1030, 910...	Ce 150 4.1 s α 139, 284; 487, 1364; 1030, 910...	Ce 151 1.0 s α 139, 284; 487, 1364; 1030, 910...	Ce 152 1.4 s α 139, 284; 487, 1364; 1030, 910...	Ce 153 >300 ns α 139, 284; 487, 1364; 1030, 910...	Ce 154 >300 ns α 139, 284; 487, 1364; 1030, 910...



Comparison

of the
bio-distribution
of different
tumor seeking
tracers

labeled with
radio-lanthanides,
 ^{225}Ac and ^{111}In

free chelates:

Citrate

EDTMP

specific tracers:

Octreotide

and

Mab

Linker:

Aminobenzyl-DTPA

G.J.Beyer, Hyperfine Interactions 129 (2000) 529.

Principle of Radioimmuno Therapy

DAUDI cells

Cell membrane

Proteins in healthy cells

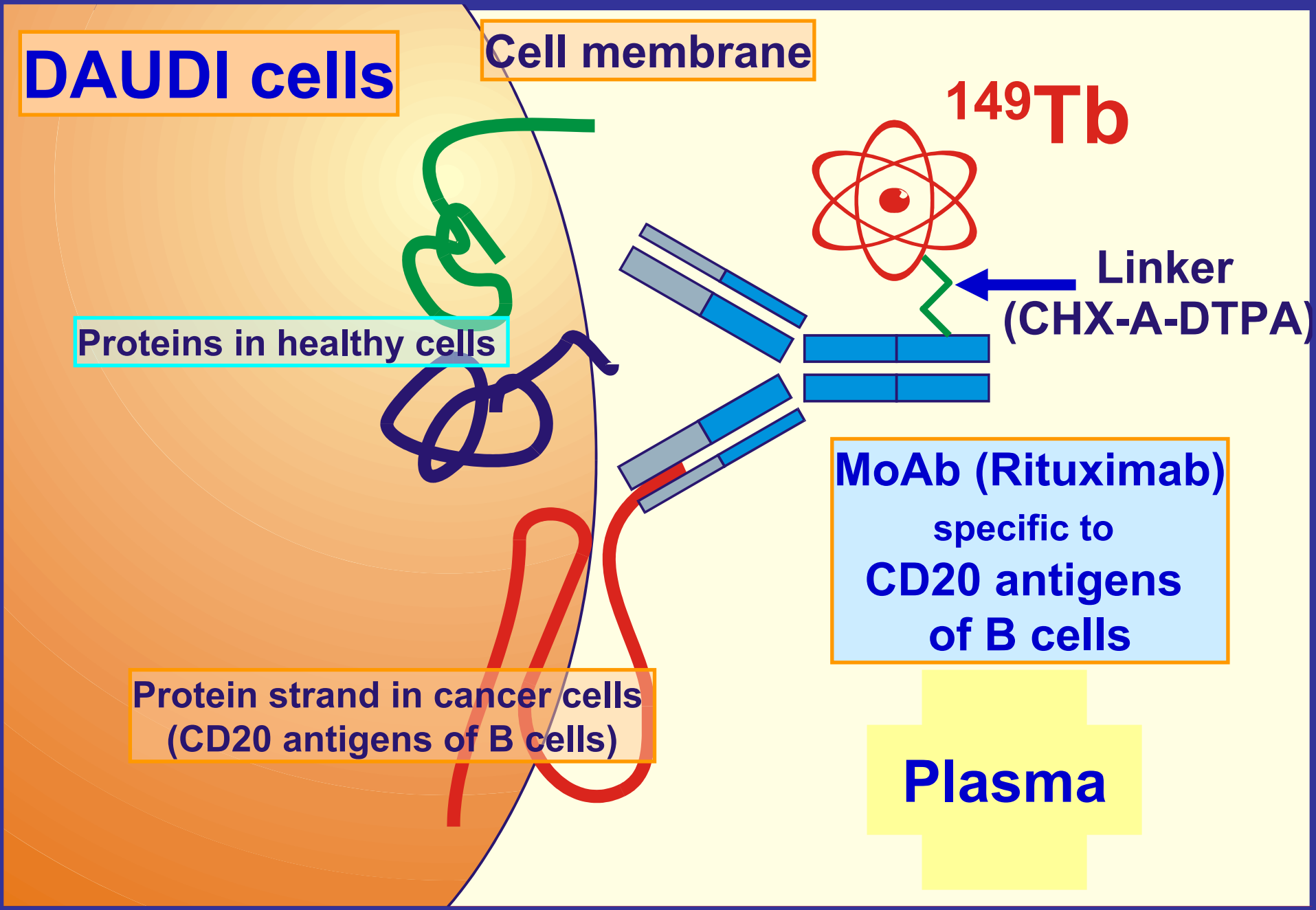
**Protein strand in cancer cells
(CD20 antigens of B cells)**

^{149}Tb

**Linker
(CHX-A-DTPA)**

**MoAb (Rituximab)
specific to
CD20 antigens
of B cells**

Plasma



$1 \cdot 10^5$ limfoma cells
injected to all mice
(Daudi cells of
Burkitt limfoma)

NO
treatment

1

2 days later the mice have been divided into 4 groups:

5 μ g MoAb
(Rituximab,
specific to CD20
antigens of B cells)

300 μ g MoAb

5 MBq ^{149}Tb -MoAb
(5 μ g MoAb)

2

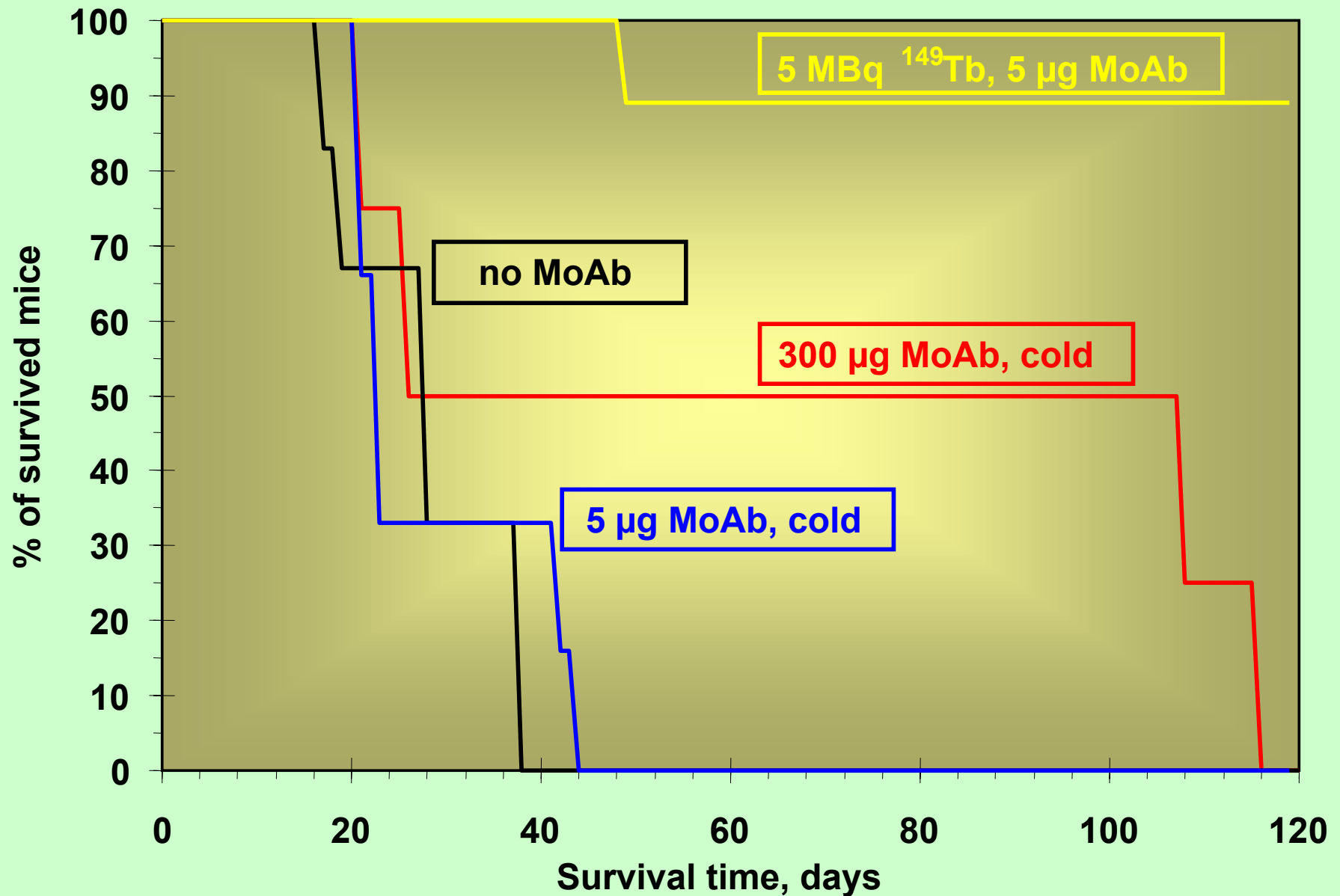
3

4

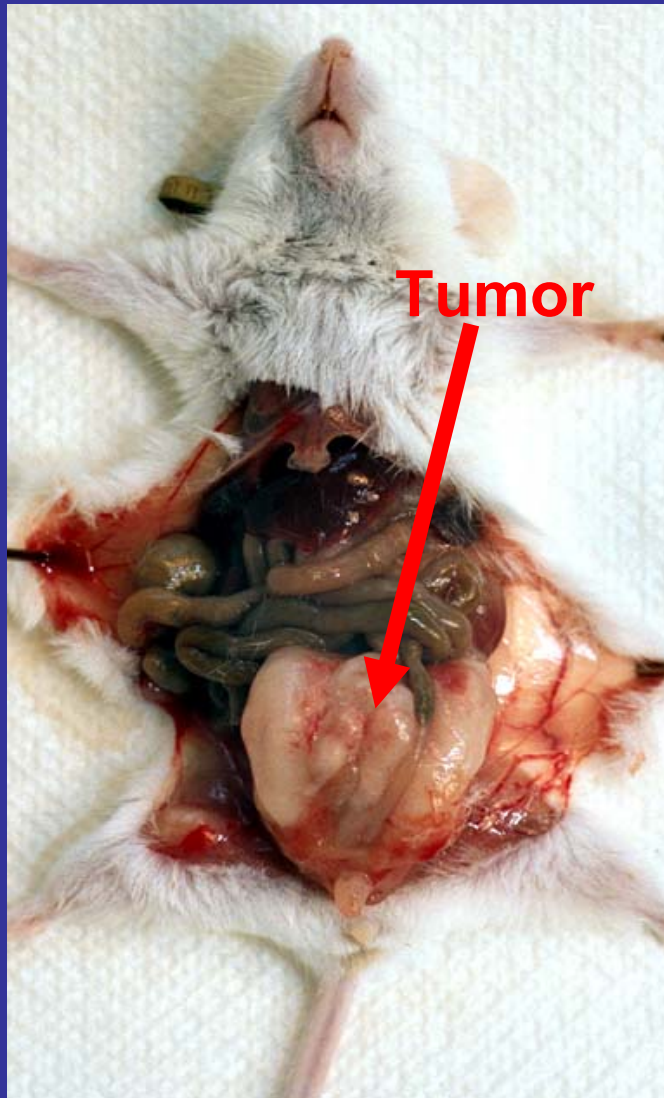
First in vivo experiment to
demonstrate the efficiency of alpha
targeted therapy using ^{149}Tb
produced at ISOLDE, Summer 2001

SCID mice (Severe
Combined
ImmunoDeficient)

Survival of SCID mice



103 d p.i.



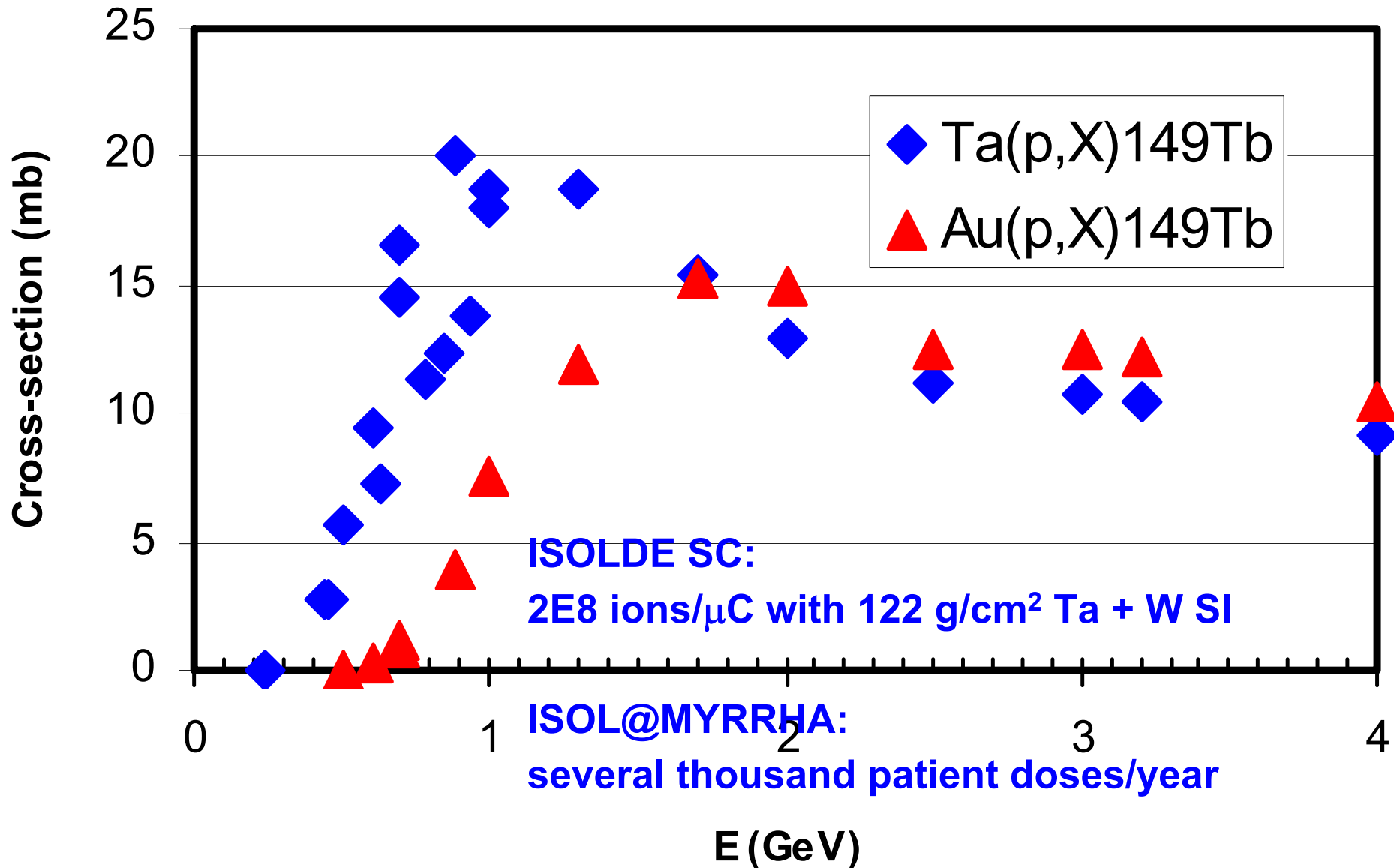
300 μ g MoAb cold

108 d p.i.

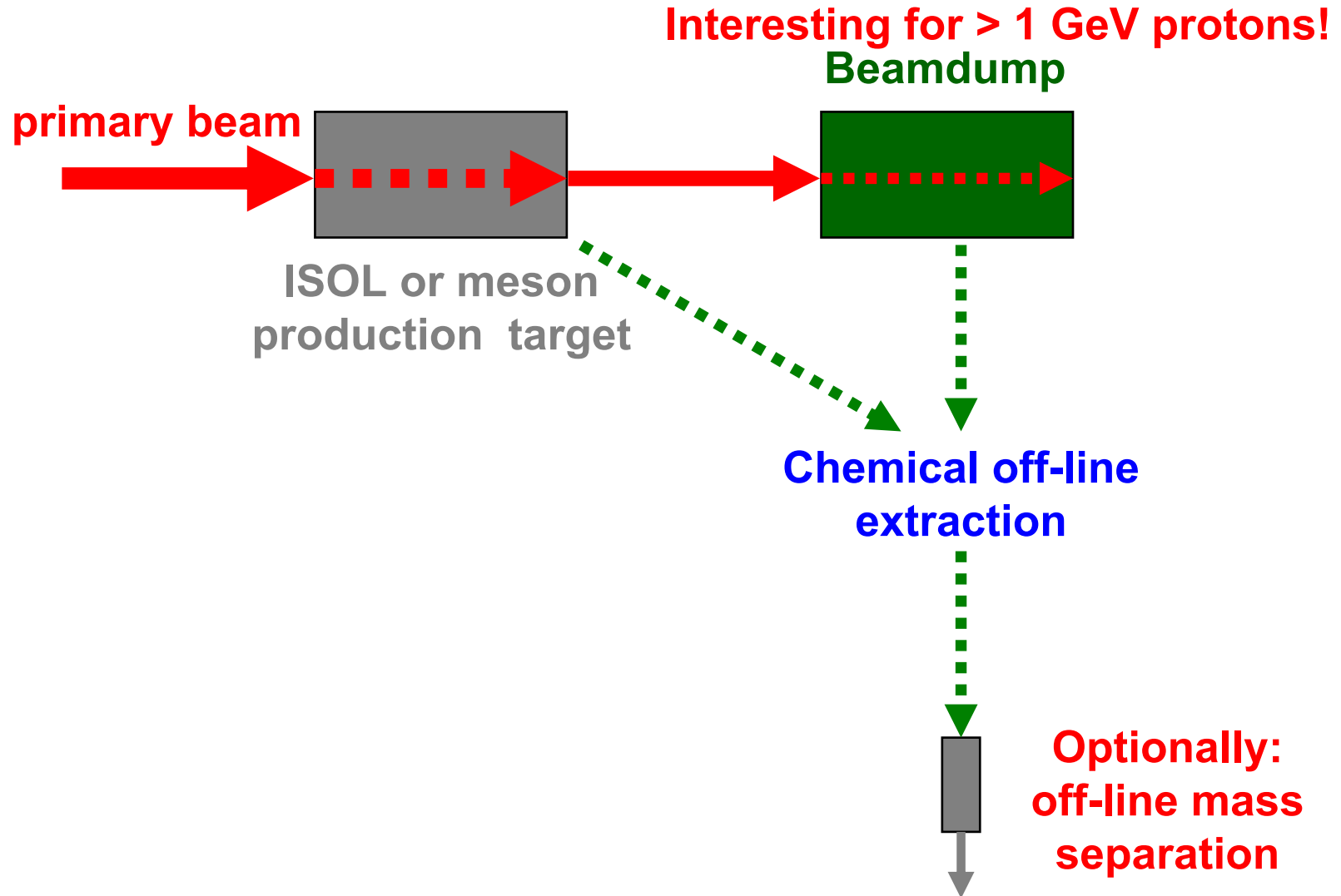


5 MBq ^{149}Tb -MoAb (5 μ g)

Spallation production of ^{149}Tb

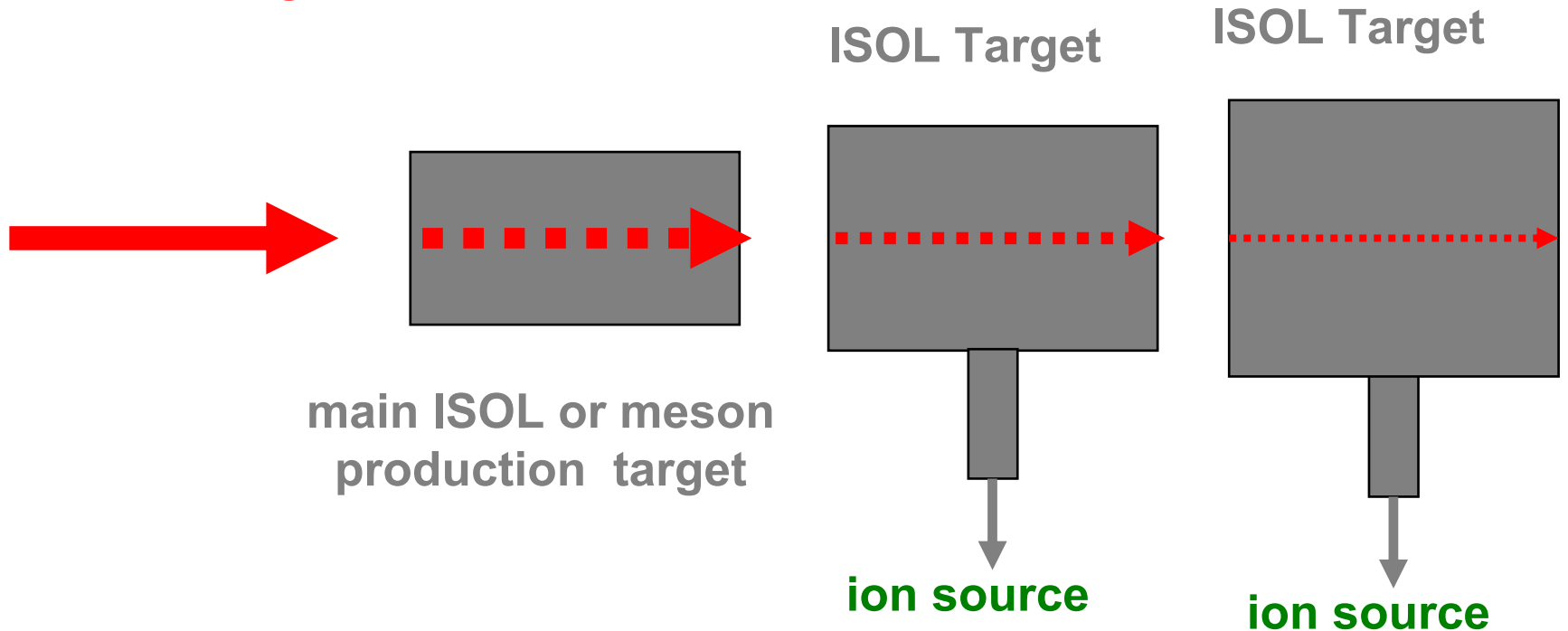


1. Off-line extraction from irradiated targets or dedicated beamdumps



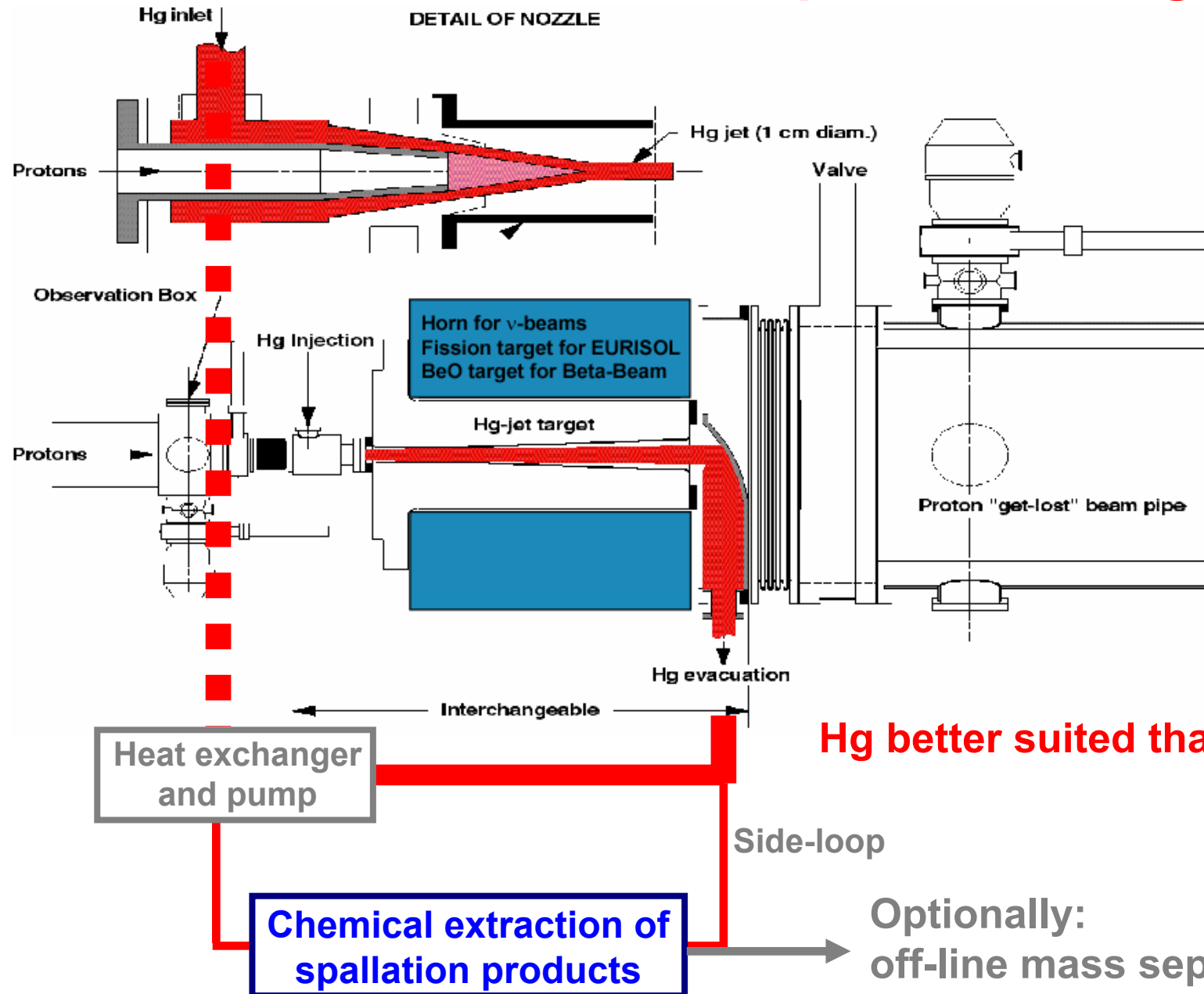
2. Dedicated ISOL target(s) at beamdump position

Interesting for > 1 GeV protons!



Extraction of mass-separated beams of short-lived isotopes for nuclear medicine

3. On-line extraction from liquid metal targets



Hg better suited than Pb/Bi!

Optionally:
off-line mass separation

Summary

- powerful accelerator is not everything
- aim for **tens of μA proton beam** rather than hundreds of μA
- **effort in instrumentation** should be in relation to effort in beam production
- most **exotic isotopes** reachable for **few elements** only
- applications with **limited count rate capability** or detection methods with high intrinsic selectivity but low efficiency compensated by **longer running times**
- driver accelerator with **low trip probability** should favor experiments relying on constant beam intensity (**scanning**)
- supply of **specific medical isotopes**?